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The Demise of Nuclear Energy?

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The Demise of Nuclear Energy?

Lessons for Democratic Control of Technology

Joseph G. Morone

Edward J. Woodhouse

Yale University Press
New Haven and London

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For our parents
Stasia and James Morone
Carolyn and Robert Morton

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Preface

This book has been a decade in the making. It began at Yale when we were graduate students, and then gradually took shape as we made other studies of technological decision making. Some of these are reported on in our earlier collaboration, *Averting Catastrophe: Strategies for Regulating Risky Technologies* (Berkeley: University of California Press, 1986).

Throughout this period we remained unsatisfied with prevailing scholarship, journalism, and public debate on nuclear power. There was criticism aplenty, of course: about citizen protests and regulatory delays, shoddy workmanship and lax management, cost overruns and plant cancellations. Although not as common, there were even sensible interpretations of particular facets of the nuclear problem. But no one seemed to offer a convincing overall appraisal of the nuclear power experience, perhaps in part because it was too early to see the technology's travails clearly and comprehensively. The pressing issues of the day, such as the accident at Three Mile Island, obscured longer-term trends and deeper problems.

As we have struggled to get beneath the surface of the controversy to understand the demise of American nuclear power at a fundamental level, four themes have helped guide us. First, we consider it obvious that humans are responsible for whether and how technologies are used, and yet it is equally apparent that technologies somehow

have a tendency to elude intelligent control. Can both these observations really be correct simultaneously? How do we make sense of the problem of autonomous technology and human agency?

Second, environmentalists are surely right in saying that catastrophic technological accidents are unacceptable. Yet nuclear advocates are equally right to criticize coal as an extraordinarily hazardous method of generating electricity. In a way, the nuclear power debate has been absurd, for who would want either coal or nuclear power as these energy sources have been employed in our lifetime? We seem to face a Hobson's choice between acid rain, climate warming, and lung disease from coal and the widespread fear, potentially catastrophic accidents, and economic losses of well over \$30 billion from nuclear power. Can't technological societies do better than that?

Third, almost everyone has a sense that there is something different about technology, that it has portentous impacts on the ways people live and therefore poses special problems of governance. But our fellow political scientists have shown little interest in studying technological decision making. Even after a decade in this field, we remain dismayed at how little scholarly attention is paid to it. A decade after the accident at Three Mile Island, social science research on nuclear power is surprisingly sparse, and it tends to focus on issues we find unexciting and secondary (like siting disputes). Have we misled ourselves about the potential theoretical yield here, or can the story of nuclear power's demise be so framed as to crystallize our intuition that the politics of technology is a distinctive phenomenon worthy of much greater scrutiny by our colleagues?

Finally, we stay in this business partly because we think that political science has something important to offer the world. Analysis should rarely play the leading role in decisions; people's values, financial constraints, habits developed through trial and error, and common sense should usually dominate. But almost everyone has been confused about nuclear power, and as the controversy has dragged on it has seemed to become more muddled rather than less. Over and over we have asked ourselves how social science scholarship could help clarify the nuclear mess. As decision theorists, we ought to be able to provide a framework useful to diverse partisans, so that they might solve the problem rather than just reiterate their positions.

We have tried to address each of these concerns. As we now

understand it, the essential lesson of the nuclear power experience pertains to the problem of technological inertia, and the blend of democratic debate and decision strategy necessary to shape and reshape technologies in accord with evolving social preferences. To put it a bit too simply, the United States failed to use these tools at a crucial time; we became fixated on one highly flawed form of nuclear power, instead of treating the technology as a tool that could be reshaped through democratic learning.

One person who did not fall into that trap was Alvin Weinberg. By no means have his views always proved correct. But more than any other nuclear decision maker he has periodically revised his thinking over almost half a century, taking account of accumulated experience, new ideas, and changing social preferences. Although unabashedly a technocrat (as certainly neither of us is), Weinberg has repeatedly emphasized the imperative that technology be socially acceptable. While most of his colleagues in the nuclear power community fell prey to habit and inertia, Weinberg continually sought new technical and organizational means that would bring to fruition his generation's dream of a safer and less exhaustible source of energy to serve humanity. We do not profess to know what the United States and the world should do about nuclear power in the twenty-first century. But the ultimate decisions will be greatly improved if more of the partisans bring to their deliberations the spirit embodied by Alvin Weinberg of technically sophisticated, democratically attuned learning from error. Though we have never met the man, this book is dedicated to him, in addition to those listed on the dedication page.

We owe debts of gratitude to dozens of scholars, policy makers, and members of the nuclear industry, only a few of whom are formally acknowledged in our footnotes as having been interviewed. In particular we thank Henry Hurwitz and Richard Alben for educating us about nuclear technology while one of us (Morone) was at General Electric; without their expertise we never would have understood the technology well enough to ask the right political questions. For extremely constructive comments on preliminary versions of the manuscript we thank Richard Barke, P. Thomas Carroll, David Collingridge, Patrick Hamlett, C. E. Lindblom, Gene I. Rochlin, Richard Sylves, Norman Vig, Aaron Wildavsky, and several anonymous reviewers. Of

many invaluable research assistants, George Narode stands out. And Marge McLeod of Rensselaer Polytechnic Institute can now breathe a sigh of relief: her outstanding word processing will not have to endure an eighth draft!

CHAPTER ONE

Introduction

Nuclear power once stood for a bright and exciting future, a tangible symbol of hope and optimism in the postwar era. What began as the dream of a handful of scientists working in wartime laboratories grew into one of the most ambitious technological efforts of the second half of the twentieth century. In scale, expense, technical challenge, and organizational complexity, it was comparable to the Apollo space program. But the outcome could not have been more different.

Whereas Apollo won wide acclaim as a source of national pride and perhaps contributed to the evolution of humanity's global consciousness, civilian nuclear power in the United States has brought mainly grief: widespread fear, huge cost overruns, utility companies stuck with partly completed reactors, and the nuclear industry in disarray. As *Forbes* noted in 1985: "The failure of the U.S. nuclear power program ranks as the largest managerial disaster in business history. . . . The utility industry has already invested \$125 billion in nuclear power, with an additional \$140 billion to come, . . . and only the blind, or the biased, can now think that most of the money has been well spent."¹ Now, after more than a decade of intense controversy, after one near miss at Three Mile Island (TMI) and a major accident in the Soviet Union, the image of nuclear power is in tatters. For many, it is a source of fear and distrust. For others, who continue

1. James Cook, "Nuclear Follies," *Forbes*, February 11, 1985, cover page.

to believe in its promise, the widespread opposition to it is a vexing example of human folly. The bitter experience raises fundamental doubts about the ability of representative government to manage complex technologies sensibly. Equally disturbing, nuclear power may illustrate a tendency for invasive new technologies to trample popular wishes.

How could the postwar hopes have been so badly off the mark? How did decades of development, several hundred billion dollars invested, and the lifelong commitment of thousands of scientists and engineers produce a technological white elephant that the American public does not want?² What went wrong with one of the epochal undertakings of our era? Just as the Vietnam War taught valuable lessons about the limits of military intervention and the fallibility of American presidents, so should any major failure offer an opportunity for society to learn. It is in fact often easier to learn from error than from success. The purpose of this book is to promote learning from the unsuccessful American experience with nuclear power.

We attempt to answer four main questions:

- What were the key decisions that led to the form of nuclear technology that has been rejected?
- Could those decisions have been shaped in ways that would have made nuclear power more acceptable to the American public?
- What does this frustrating experience teach us about the larger question of how democracy and technology interact?
- What does our present vantage point suggest about future energy policy: is a more acceptable form of nuclear power still conceivable as a response to rapidly growing concerns about the greenhouse effect?

When the issue is framed in this way, we believe that reflective observers—both for and against nuclear power—will find far more to agree about than either side ordinarily suspects. Shared understandings about errors of the past may or may not translate into improved policy for nuclear power *per se*. But learning from mistakes in nuclear policy making stands a realistic prospect of enhancing society's col-

2. The term *white elephant* was suggested by Otto Keck in "A Theory of White Elephants: Asymmetric Information in Government Support for Technology," *Research Policy* 17 (1988).

lective intelligence and improving its ability to make wiser technological choices in the future. People may come to think more clearly about the overall enterprise of intelligent, publicly acceptable governance.

A Politically Unsafe Technology

Spirited debate about whether nuclear power is sufficiently safe has been going on since the mid-1960s. Many observers believe that the United States is behaving irrationally in rejecting the technology.³ The nuclear industry's safety record, they argue, is better than that of any other major industry. Even the accident at Three Mile Island was no more damaging to public health and safety than a minor car crash, according to the independent presidential commission that studied the accident.⁴ Nuclear advocates point out that France, Japan, and other nations rely increasingly on nuclear power. Moreover, the risks from other sources of energy are substantial: coal emissions lead to acid rain and warming of the earth's atmosphere, aging dams pose a growing safety hazard, and reliance on foreign oil creates economic and political instability.

But other thoughtful observers are just as eloquent in damning nuclear power. They point to a long list of poorly managed plants, construction flaws, operators asleep on the job, and a thoroughly muddled regulatory system allegedly biased toward the industry it oversees.⁵ They reason that the nuclear technological system is so complex that its behavior cannot be predicted, and ask: What if something unanticipated goes wrong? What if deadly radioactive material somehow escapes into the environment? It happened at Chernobyl; it almost happened at Three Mile Island. With so many unknowns and the potential for catastrophe, why take the risk?

As will become apparent, we do not take sides in this debate; it is not necessary to do so. For whatever the merits of the opposing

3. One thoughtful expression of this view can be found in Bernard L. Cohen, *Before It's Too Late: A Scientist's Case for Nuclear Energy* (New York: Plenum, 1983).

4. President's Commission on the Accident at Three Mile Island, *The Need for Change: The Legacy of TMI* (Washington: U.S. Government Printing Office, 1979).

5. For a fair-minded discussion of these and many other aspects of problems facing nuclear power see U.S. Congress, Office of Technology Assessment, *Nuclear Power in an Age of Uncertainty*, OTA-E-216 (Washington, 1984; hereafter cited as OTA, 1984).

arguments, enough of the American public is sufficiently worried about nuclear power to make it a politically unsafe technology. It has become a source of fear and anxiety, and by the late 1980s a substantial majority of the public preferred to turn away from it. Further, utilities find nuclear power financially unattractive, so the issue is settled for the foreseeable future.

Yet for most of the nuclear age the public supported nuclear power. It was not until the accident at Three Mile Island in 1979 that a majority became opposed to further construction and licensing of nuclear plants.⁶ One executive for a utility company said the effect of Three Mile Island was "like having your wife catch you in bed with another woman. Even if the marriage stays together, things are never the same again. The faith that makes the relationship work is gone."⁷

By 1983 only about 37 percent of the American public favored more nuclear power, and 51 percent opposed it.⁸ After the accident at Chernobyl in 1986, as many as 75 percent of those questioned in some polls opposed construction of nuclear power plants within five miles of their homes. Some 55 percent believed it likely that there could be an accident in the United States similar to that at Chernobyl. And two-thirds of the public favored cutting back nuclear plant operations until stricter safety regulations could be put into effect.⁹

Largely as a result of concerns about safety, nuclear plants have grown steadily more expensive; and by the 1980s a new nuclear facility was estimated to cost 65 percent more than an equivalent coal-fired plant.¹⁰ This is partly because planning and building a plant can take twelve to fourteen years, during which the utility has to pay

6. For a review of opinion polling at the time see Robert C. Mitchell, "Public Response to a Major Failure of a Controversial Technology," in David L. Sills et al., eds., *Accident at Three Mile Island: The Human Dimensions* (Boulder: Westview, 1982), pp. 21-38.

7. Quoted in Peter Stoler, *Decline and Fall: The Ailing Nuclear Power Industry* (New York: Dodd, Mead, 1985), p. 116.

8. The best overall appraisals of public opinion to 1983 on nuclear power are William R. Freudenberg and Eugene A. Rosa, eds., *Public Reactions to Nuclear Power: Are There Critical Masses?* (Boulder: Westview, 1984); and Stanley Nealey et al., *Public Opinion and Nuclear Energy* (Lexington, Mass.: Lexington Books, 1983).

9. Poll results by CBS and Gallup from spring 1986 were reviewed in *New York Times*, "Poll Finds Revival of Nuclear Fears," July 26, 1986, p. 4. See also Christopher Flavin, *Reassessing Nuclear Power: The Fallout from Chernobyl* (Washington: Worldwatch Institute, 1987).

10. Charles Komanoff, *Power Plant Cost Escalation: Nuclear and Coal Capital Costs, Regulation, and Economics* (New York: Van Nostrand Reinhold, 1981).

interest on the money borrowed to start the process. This is more than twice as long as it takes to build a coal-fired plant, and the difference is due largely to regulatory hurdles and court challenges from environmental groups. As a result, "no utility executive would dare propose to a board of directors that they begin to construct a new nuclear power plant. Too many utilities are losing their shirts on nuclear reactors."¹¹

In fact, utilities have canceled more than a hundred orders for reactors, many of which were already under construction. The Washington Public Power Supply System defaulted on more than \$2 billion of bonds after canceling four nuclear plants, and the Marble Hill plant in Indiana was canceled after some \$2.5 billion had been expended on it. The Shoreham reactor in New York and the Seabrook plant in New Hampshire, completed at a cost of more than \$5 billion each, may never operate, because of local opposition.¹² According to one thoughtful professor of nuclear engineering:

Nuclear power is on its way out in the United States. The current technology has failed in the U.S. marketplace, and it will not be revived. . . . All the plants presently under construction were ordered before 1974, and no utility has plans to order another for as far into the future as it can see. In a few years the oldest nuclear plants will begin to be retired, . . . nuclear power will gradually play a less important role in the nation's economy, and in 25 or 30 years it will be completely negligible.¹³

Reviewing the dismal financial prospects, another observer puts it succinctly: "For the U.S., nuclear power is dead."¹⁴

Although circumstances could change, we concur that a phase-out of nuclear technology is in process.

11. Russ Manning, "The Future of Nuclear Power," *Environment* 27 (May 1985): 12–18, 31–37; the quotation is from p. 13. See also Graham Allison et al., "Governance of Nuclear Power" (Washington: President's Nuclear Safety Oversight Committee, 1981).

12. Wayne H. Sugai, *Nuclear Power and Ratepayer Protest: The Washington Public Power Supply Crisis* (Boulder: Westview, 1987); *IEEE Spectrum* 24 (November 1987), special section on Shoreham; Donald W. Stever, *Seabrook and the Nuclear Regulatory Commission* (Hanover, N.H.: University Press of New England, 1980).

13. Lawrence M. Lidsky, "Safe Nuclear Power," *New Republic*, December 28, 1987, pp. 20–23; the quotation is from p. 20.

14. Cook, "Nuclear Follies," p. 82.

What Ails Nuclear Power?

Explanations of what has gone wrong abound. Many observers emphasize shortcomings in the government's or the nuclear industry's approach to the technology. For example, Wildavsky suggests that the Nuclear Regulatory Commission (NRC) unnecessarily drives up the costs of nuclear power and confuses its priorities by making so many regulations that it is impossible to monitor and enforce them all.¹⁵ More generally, Daniel Ford's *Cult of the Atom* asserts that federal regulatory agencies "Were able to ignore what they did not wish to believe and were inclined to cover up everything discreditable. . . . The agencies disregarded the warning signs—the numerous reports of trouble at operating plants—as well as the advice from . . . experts who questioned the official safety assurances."¹⁶

Many have argued that decision making in the early years of atomic power was monopolized by a "cozy subgovernment" that effectively excluded potential critics.¹⁷ The absence of pluralism led to overzealous promotion of nuclear energy by Congress and the Atomic Energy Commission (AEC). The enduring legacy of this arrangement is that "by denying to those outside the club the right to question their actions, the proponents of nuclear power in industry and government damaged their own credibility and enhanced the legitimacy and power of their critics."¹⁸ Some form of the theme "not enough democracy" is echoed in perhaps half the social science treatments of the nuclear experience.¹⁹

15. Aaron Wildavsky, "The Assessment of Safety Goals and Achievements in Complex Technological Systems: The Integration of Technological and Institutional Considerations" (unpublished manuscript prepared for the U.S. Nuclear Regulatory Commission, September 1983).

16. Daniel Ford, *The Cult of the Atom* (New York: Simon and Schuster, 1982), p. 237.

17. James R. Temples, "The Politics of Nuclear Power: A Subgovernment in Transition," *Political Science Quarterly* 95 (1980): 239–260.

On early problems caused by the position of the Atomic Energy Commission as both regulator and promoter of nuclear power see George T. Mazuzan and J. Samuel Walker, *Controlling the Atom: The Beginnings of Nuclear Regulation, 1946–62* (Berkeley: University of California Press, 1984). For an overview of later problems see Edward J. Woodhouse, "The Politics of Nuclear Waste Management," in Charles A. Walker et al., eds., *Too Hot to Handle? Social and Policy Issues in the Management of Radioactive Wastes* (New Haven and London: Yale University Press, 1983), pp. 151–183.

18. Irvin C. Bupp and Jean-Claude Derian, *The Failed Promise of Nuclear Power: The Story of Light Water* (New York: Basic Books, 1978; reissued with additional material as *The Failed Promise of Nuclear Power: The Story of Light Water*, 1981), p. 193.

19. See for example the discussion of "alienation and augmentation of conflict"

A different note was struck by investigations following the accident at the Three Mile Island nuclear plant in 1979, most of which focused on management by the utility company and inadequate oversight of the utilities by the Nuclear Regulatory Commission. For example, the Kemeny Commission appointed by President Carter found poorly trained plant operators, confusing control panels, and shoddy maintenance by the utility company.²⁰

There have been many other criticisms of nuclear power,²¹ some of which are given below:

resulting from "ritualistic" citizen participation in licensing hearings in Steven L. Del Sesto, *Science, Politics, and Controversy: Civilian Nuclear Power in the United States, 1946-1974* (Boulder: Westview, 1979), p. 220. A variant of the general theme is sounded by Mark Hertsgaard, who argues that "it was the predictable and repeated abuse of this secrecy [originating in the connection with military nuclear programs] that ultimately destroyed Americans' faith in nuclear power," in *Nuclear Inc.: The Men and Money behind Nuclear Energy* (New York: Pantheon, 1983), p. 250.

20. See chapter 5 for a brief description of the accident and the investigations that it sparked. A more detailed analysis is in Joseph G. Morone and Edward J. Woodhouse, *Averting Catastrophe: Strategies for Regulating Risky Technologies* (Berkeley: University of California Press, 1986), chap. 3. On the human dimensions see Sills et al., *Accident at Three Mile Island*.

21. In addition to works cited elsewhere in this chapter, the following represent overtly partisan criticisms of nuclear power after Three Mile Island: Karl Grossman, *Cover Up: What You Are Not Supposed to Know about Nuclear Power* (Sag Harbor, N.Y.: Permanent Press, 1980); Fred Hoyle and Geoffrey Hoyle, *Commonsense in Nuclear Energy* (San Francisco: W. H. Freeman, 1980); Daniel F. Ford, *Three Mile Island: Thirty Minutes to Meltdown* (New York: Penguin, 1982); Michio Kaku and Jennifer Trainer, eds., *Nuclear Power, Both Sides: The Best Arguments for and against the Most Controversial Technology* (New York: W. W. Norton, 1982); Kristen S. Shrader-Frechette, *Nuclear Power and Public Policy*, 2d ed. (Boston: Kluwer Academic, 1983); Judith Cook, *Red Alert: The Worldwide Dangers of Nuclear Power* (Sevenoaks, England: New English Library, 1986); Union of Concerned Scientists, ed., *Safety Second: The NRC and America's Nuclear Power Plants* (Bloomington: Indiana University Press, 1987).

For less partisan treatments, some nevertheless with strong judgments about errors in nuclear policy, see S. David Aviel, *The Politics of Nuclear Energy* (Lanham, Md.: University Press of America, 1982); Andrew Blowers and David Pepper, eds., *Nuclear Power in Crisis: Politics and Planning for the Nuclear State* (New York: Nichols, 1987); Joseph Camilleri, *The State and Nuclear Power: Conflict and Control in the Western World* (Seattle: University of Washington Press, 1984); Jim Falk, *Global Fission: The Battle over Nuclear Power* (New York: Oxford University Press, 1982); Christopher Flavin, *Nuclear Power: The Market Test* (Washington: Worldwatch Institute, 1983); Flavin, *Reassessing Nuclear Power: The Fallout from Chernobyl* (Washington: Worldwatch Institute, 1987); Martin J. Plasqualetti and K. D. Pijawka, eds., *Nuclear Power: Assessing and Managing Hazardous Technology* (Boulder: Westview, 1984); William Walker and Måns Lönnroth, *Nuclear Power Struggles* (London: George Allen & Unwin, 1983); Phil Williams, *The Nuclear Debate: Issues and Politics* (Boston: Routledge and Kegan Paul, 1984); William C. Wood, *Nuclear Safety, Risks and Regulation* (Washington: American Enterprise Institute, 1983).

1. Inadequate quality control by construction managers, coupled with shoddy work by construction crews
2. Unpredictability in the regulatory process
3. Lack of openness on the part of the industry and the regulatory agencies concerning problems
4. Large reactors built too soon
5. Inexperienced and inadequately skilled professional personnel for some utilities
6. Overlapping and conflicting authority of the utility company, the reactor vendor, the architecture and engineering firm, and the contractor
7. Mismanagement by the Nuclear Regulatory Commission
8. Failure of the Joint Committee on Atomic Energy to oversee effectively the Atomic Energy Commission and the industry
9. Inappropriateness of the hearing process by which reactors were licensed
10. Conflict of interest within the Atomic Energy Commission, which both promoted nuclear energy and was to regulate it
11. Inadequate knowledge of the public.²²

Many of these criticisms fall into what might be called the mismanagement theory: the demise of American nuclear power could have been avoided if only the reactor vendors, construction firms, utilities, and regulatory agencies had done a better job. Another type of explanation focuses more on the basic economic issues. Komanoff's study of cost problems in nuclear power essentially concludes that nuclear reactors required more safety precautions than initially recognized, government regulators discovered this and imposed appropriate regulations, and the resulting costs were more than utilities and their financing sources were willing to bear. The cost problems were exacerbated by high rates of inflation during this period, a deterioration in the utility companies' ability to raise funds in the bond and stock markets as their total indebtedness grew, and the unwillingness of public commissions in most states to allow utilities to charge customers for plants under construction. Moreover, the utili-

22. Most of these criticisms can be found in some form in OTA, 1984, and Ford, *Cult of the Atom*.

ties were faced with excess generating capacity, because use of electricity by homes and businesses grew much more slowly than expected after the OPEC oil embargo of 1973 and the subsequent price increases.²³

Another genre of analysis points at more fundamental issues having to do with the technology itself. For example, if there is a prevailing commonsense hypothesis among the general public, it is that nuclear power is inherently too dangerous. In its purest form, this view holds that nuclear power poses an unwarranted risk no matter how careful the regulation, how competent the construction, and how diligent the utility companies' procedures for training operators and maintaining the reactors.

A second fundamental critique emphasizes the scale and complexity of technology and the consequent difficulty of effective design, management, and regulation. Perhaps the most interesting argument along these lines is offered by a British analyst of technology policy, David Collingridge. Recognizing that mistakes are inevitable in all complex human endeavors, he argues that "what really separates nuclear power from other innovations is not the existence of misjudgement, wishful thinking, bad management, mistaken forecasts and plain bad luck, but the extraordinarily high cost which these errors have had" (*italics in original*).²⁴ The costliness of the errors was due primarily to the huge financial investment and the many years required to construct a large nuclear plant. Thus a great deal of time and money had been spent before it became obvious that projections from the mid-1960s about cost and reliability were inaccurate. Some seventy power plants had been wholly or substantially constructed in the United States by 1979, and it was too late to escape high costs from the error. Collingridge argues that with a technology like nuclear power this inflexibility was unavoidable, and led directly to its troubled history.²⁵

23. Komanoff, *Power Plant Cost Escalation*, is the most detailed analysis. See also U.S. Department of Energy, *Nuclear Power Plant Cancellations: Causes, Costs, and Consequences*, DOE/EIA-0392 (Washington, 1983); John L. Campbell, "The State, Capital Formation, and Industrial Planning: Financing Nuclear Energy in the United States and France," *Social Science Quarterly* 67 (1986): 707-721; Leonard G. Brooks and Homa Motamen, eds., *The Economics of Nuclear Energy* (London and New York: Chapman and Hall, 1984).

24. David Collingridge, *Technology in the Policy Process: Controlling Nuclear Power* (New York: St. Martin's, 1983), p. 46.

25. For further development of the argument see David Collingridge, *The Social*

Charles Perrow offers a related argument, suggesting that “no matter how effective conventional safety devices are, there is a form of accident that is inevitable.”²⁶ Technologies like nuclear power have many different components that interact in unpredictable ways, and the overall nuclear plant is so “tightly coupled” that small failures in one part of the system can lead to bigger problems elsewhere in the system. He sees no way to free nuclear power from vulnerability to this kind of “system accident.”

Finally, social scientists offer a number of explanations for why Americans have rejected nuclear power. Social psychologists find that the public tends to accept activities that are familiar, voluntary, and do not pose catastrophic risks—and to reject those with the opposite characteristics, like nuclear power.²⁷ Wildavsky and Douglas trace to environmental groups what they perceive as excessive urges for environmental purity, and connect this zeal and influence with distinctive elements of American political culture.²⁸ Rothman and Lichter suggest that “journalists’ ideologies influence their coverage of nuclear energy and that media coverage of the issue is partly responsible for public misperceptions of the views of scientists.”²⁹

A Different Question

Each of the above explanations has merit. There can be little doubt that “the perceptions of all of us, liberals and conservatives (and others) alike, are influenced by nonrational factors.”³⁰ We take that for granted. But representative democracies are fairly adept at compensating for “nonrational” factors. Indeed, good public policy consists essentially of adapting to semirational aspects of political life, just as a successful economy adapts to the vagaries of shifting con-

Control of Technology (London: Frances Pinter, 1980); Collingridge, “Lessons of Nuclear Power,” *Energy Policy* 12 (March 1984): 46–67.

26. Charles Perrow, *Normal Accidents: Living with High-Risk Technologies* (New York: Basic Books, 1984); the quotation is from p. 3.

27. Baruch Fischhoff et al., *Acceptable Risk* (New York: Cambridge University Press, 1984).

28. Aaron Wildavsky and Mary Douglas, *Risk and Culture* (Berkeley: University of California Press, 1981).

29. Stanley Rothman and S. Robert Lichter, “Elite Ideology and Risk Perception in Nuclear Energy Policy,” *American Political Science Review* 81 (June 1987): 383–404; the quotation is from p. 383.

30. *Ibid.*, p. 395.

sumer preferences. The genius of democracy is its ability to shove, nudge, and mold public policy gradually and incrementally in ways that loosely conform to public opinion—while also helping to shape opinion. We wonder why that did not happen here, and none of the existing analyses quite provides an answer.

Although it is fascinating to document the ills of the industry and trace the roots of the American public's rejection of nuclear power, that is not our objective; altogether, the explanations already available do this well. But if our predicament is fairly clear, it is by no means obvious how we got into it or how it might have been avoided. So although we draw on many of the available critiques, in this book we want to pose new questions: Why did the American political system persist in producing a technology that was proving psychologically and financially unacceptable? How did decades of work and billions of dollars produce such a white elephant? What prevented policy on nuclear power from responding to shifts in the preferences of interest groups, the news media, and voters?

However severe and contentious the problems that new technologies raise, the American political system is typically able to reach a compromise widely perceived as satisfactory, or at least a decision the losers find tolerable. What prevented the nuclear power controversy from being transformed into an ordinary political issue that could be resolved through the usual logrolling and compromise? We believe that to be able to answer this question is to understand what went wrong with nuclear power in the United States, for the failure here is not primarily with a technology but with a decision-making process that is supposed to evolve solutions to complex problems. Questions of this type have long captured the attention of political scientists, historians, and others studying Americanization of the Vietnam War, the ill-fated Bay of Pigs episode, and other important decision-making endeavors.³¹ But policy making about nuclear power has not yet been subjected to sustained inquiry along these lines.

31. See for example Graham T. Allison, *Essence of Decision: Explaining The Cuban Missile Crisis* (Boston: Little, Brown, 1968); Ernest R. May, *The Lessons of the Past: The Use and Misuse of History in American Foreign Policy* (New York: Oxford University Press, 1973); Leslie H. Gelb with Richard K. Betts, *The Irony of Vietnam: The System Worked* (Washington: Brookings Institution, 1979); Lloyd Etheredge, *Can Governments Learn? American Foreign Policy and Central American Revolutions* (New York: Pergamon, 1985); Richard E. Neustadt and Ernest R. May, *Thinking in Time: The Uses of History for Decision-Makers* (New York: Free Press, 1986).

In pursuing this line of analysis our method will be patient and indirect. We ask the reader to explore with us the evolution of American nuclear power from 1944 to the present, focusing on three sets of crucial choices: the type of reactor that came to dominate the nuclear industry, the institutional structure (competitive private enterprise), and the safety strategies. Early chapters retrace the sequence of decisions by which these components of the nuclear power enterprise developed. Then we ask whether the key elements were in some sense inevitable, or whether they might have been structured differently enough to create a more acceptable nuclear power industry. We find that the emergence of an unacceptable form of nuclear power could almost certainly have been avoided.³²

This is a reassuring finding in that it suggests room for doing better in the future. But it is sobering to find that with one critical exception, the main decisions in the evolution of nuclear power look relatively defensible, given the information and goals of the policy makers (and public) at the time. Individually reasonable choices produced an irrational collective outcome. And just as with arms races, the recognition of problems did not lead to a cure, as the United States clung to an unworkable approach long after its flaws became apparent.

Thus the unhappy experience with nuclear power was no accident; it was the product of deliberate decisions, and there is reason to fear a repetition. Can we learn to prevent technologies from helping lead the polity in unacceptable directions? And can we improve the use of popular control to avoid misshaping technologies, and their ultimate rejection at high cost?

A Worldwide Trend?

In the late 1970s the travails of nuclear power afflicted the United States primarily, and sometimes American advocates of the technology still speak as if their nation were the only "irrational" one.³³ Not

32. On other malleable technologies see Wiebe E. Bijker, Thomas Parke Hughes, and Trevor Pinch, eds., *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology* (Cambridge: MIT Press, 1987).

33. "Even though the rest of the industrialized world is investing in nuclear power, we are being convinced that we can do without it." Robert W. Deutsch, *Nuclear Power: A Rational Approach* (Columbia, Md.: GP Courseware, 1987), p. 91.

so. After the accident at Three Mile Island in 1979 civilian nuclear power became an extremely controversial issue in Western Europe; at huge demonstrations, environmental protesters chanted "Pennsylvania is everywhere."³⁴ The accident at Chernobyl in 1986 provided further impetus for antinuclear sentiments, as a result of which most nations have scaled back their nuclear programs (table 1.1), and many

Table 1.1 Current Status of Nuclear Power in Western Europe

Austria	National referendum in 1978 terminated nuclear program, abandoning a plant nearly ready for operation.
Belgium	No plants under construction or planned; 8 mid-size plants operating.
Denmark	Nonnuclear. Has requested Sweden to close down its plant 30 miles outside Copenhagen.
Finland	4 plants operating, none planned.
France	49 plants operating, 14 under construction. Slowdown from 6 orders per year to 1, due to overcapacity. No construction starts in 1986-87.
Italy	Safety concerns and strong local opposition have led to abandonment of new construction. Only 3 plants operating.
Netherlands	2 small plants in operation; plans for 2 others indefinitely postponed after Chernobyl; strong opposition movement.
Spain	8 plants operating, 2 under construction; 5 nearing completion were mothballed or canceled in 1983 at a cost of \$8 billion. Socialist government and public oppose heavier reliance on nuclear power.
Sweden	Public referendum in 1980 mandated a gradual phase-out of the nation's 12 operating plants. None planned or under construction.
Switzerland	5 mid-size plants operating, none planned or under construction. Public opposed to more.
United Kingdom	38 plants operating, 4 under construction, but only 1 ordered in the 1980s owing in part to strong political opposition, including that of the Labour Party.
West Germany	21 plants operating, 4 under construction, but mounting political opposition and slowed demand have imposed a moratorium in the 1980s.

Source: *Nuclear Power Reactors in the World*, IAEA-RDS-2/7 (Vienna: International Atomic Energy Agency, 1987).

34. Dorothy Nelkin and Michael Pollak, *The Atom Besieged: Extraparliamentary Dissent in France and Germany* (Cambridge: MIT Press, 1981), p. 1.

governments face opposition movements potentially strong enough to close down some plants currently in operation. By 1989 Japan and France had become the only major representative democracies with plans for substantially increased reliance on nuclear power.³⁵

The rejection of nuclear power has been widespread. The first shift in this direction came in Sweden, where a minor party suddenly came to prominence in 1976 by opposing nuclear power. In a referendum in 1980 it was decided to phase out the nation's twelve nuclear power plants, even though they generate half of Sweden's electricity. Italy's governing coalition fell apart in 1987 and 1988, in part because of the nuclear issue; the result, according to a prominent Italian physicist, is that "nuclear power based on existing technology is a closed chapter in this country. It doesn't have a future."³⁶ Even in West Germany, long in the forefront of European nuclear power efforts, political parties representing half the national vote now have taken antinuclear stances, and because only two new reactors have been ordered during the 1980s a *de facto* moratorium on nuclear construction is in effect there also.

Overall, the European nuclear industry is in retreat. As one senior official of the European Community remarked, "It has moved from being the darling of the modern age to the great menacer and polluter."³⁷ The demise of nuclear power in the United States thus appears to have been part of a much wider trend rather than an isolated case.

The Exceptions

Why have Japan and France escaped this trend? Although a thorough study of this question is well beyond the scope of this book, in broad outline there is no mystery about the Japanese and French exception. Some observers have argued that the difference in outcomes is due to energy supplies. Compared with Japan and France, the United States has abundant alternative sources of coal, oil, and natural gas, and depends on imported oil as a matter of convenience rather than an absolute lack of other options. In contrast, Japan depended almost entirely on foreign oil before launching its aggressive

35. Although most of Canada relies on hydropower and electricity generated by fossil fuel, the province of Ontario has a large nuclear program that will probably expand somewhat further.

36. *Business Week*, May 16, 1988, p. 112.

37. *Ibid.*

research and development program in nuclear power and alternative fuels. France also has quite limited domestic energy resources.

So whereas a new energy source like nuclear power represented something of a luxury for the United States, it was nearly a necessity in France and Japan, where decision makers were more willing to accept the new source of energy, even with its unappealing attributes. According to this argument, it is not so much that the French and Japanese find nuclear power attractive, as that they find the alternative more unattractive.³⁸ This explanation helps account for the French and Japanese exception, but it does not explain the rejection of nuclear power by so many European nations with limited domestic resources of fossil fuel. The rejection of nuclear power by countries like Sweden, Italy, and apparently even West Germany suggests that something more is at work here.

The more important reason for the French and Japanese exception lies in the nature of their political systems. To put it bluntly, they are among the least open to popular influence of any of the world's representative systems of government. Governance of nuclear technology has "worked" in France and Japan precisely because policy makers have not had to shape the technology to suit public preferences. Germany's pronuclear chancellor Helmut Schmidt said in the late 1970s, "In our democratic system based on public participation, nuclear energy cannot be implemented without broad public consent."³⁹ Not so in France or Japan, where governments have considerable latitude to implement policy without such public consent. Thus the massive shift to nuclear power was announced by the president of France in 1974 "as a fait accompli, leaving no room for meaningful parliamentary debate."⁴⁰ Nuclear power did become the focus of intense public opposition in France during the late 1970s, when surveys showed almost an even split between those for and against developing the technology. This was a higher percentage of opposition than in the United States at that time. But the French government

38. The willingness to accept risks is roughly proportionate to perceptions of the benefits thereby achieved; see Fischhoff et al., *Acceptable Risk*.

39. *Frankfurter Allgemeine Zeitung*, May 2, 1979, quoted in Nelkin and Pollak, *The Atom Besieged*, p. 197.

40. Nelkin and Pollak, *The Atom Besieged*, p. 2. On the French antinuclear movement see Alain Touraine et al., *Anti-Nuclear Protest: The Opposition to Nuclear Power in France*, trans. Peter Fawcett (New York: Cambridge, 1983).

effectively ignored the criticism, and by the end of the decade the French antinuclear movement had lost much of its intensity.

There are particular structural reasons for the disenfranchisement of the French opposition. As Nelkin and Pollak put it, "How critics actually confront their government depends on legal and administrative arrangements, available participatory channels, and anticipated government reactions."⁴¹ Thus the effectiveness of an anti-nuclear movement depends largely on the accessibility of a nation's government. The U.S. government, for example, creates many more points of access for dissident groups than do the highly centralized French and Japanese systems. In New York State, Gov. Mario Cuomo and local government officials on Long Island were able to block operation of the completed Shoreham nuclear plant, essentially overruling a license granted by the federal Nuclear Regulatory Commission. Except perhaps for the mayor of Paris, it is impossible to conceive of a French local or regional official successfully opposing national leadership in this way.

American interest groups also have multiple access points within the national government. Partisans blocked in one house of Congress can often gain access to the other. And if one committee or subcommittee is not sympathetic, others among more than a dozen with partial authority over nuclear power might be. Unlike for example the French Chamber of Deputies, the U.S. Congress is a powerful counterweight to the executive branch.

Even where elected officials and bureaucrats are unreachable in the United States, the courts will surely offer a haven. The dense thicket of administrative rules by which nuclear regulators must abide affords ample scope for opponents to win injunctions and rehearings. Although the argument may eventually be lost on the merits, in the nuclear case it has often been sufficient for antinuclear groups to slow the licensing and start-up process.⁴² The German court system, decentralized like the American one, played a similar role. Ambiguities in the Atom Law opened the way for judicial activism, and some

41. Nelkin and Pollak, *The Atom Besieged*, p. 5; Mary D. Davis, *The Military-Civilian Nuclear Link: A Guide to the French Nuclear Industry* (Boulder: Westview, 1988).

42. A general overview of environmental issues in the courts can be found in Lettie M. Wenner, *The Environmental Decade in Court* (Bloomington: Indiana University Press, 1982). See also Norman Vig, "The Courts: Judicial Review and Risk Assessment," in Susan G. Hadden, ed., *Risk Analysis, Institutions, and Public Policy* (Port Washington, N.Y.: Associated Faculty Press, 1984), pp. 60-79.

German judges decided that safety took precedence over economics; they also opted for a literal interpretation of the Atom Law's provision requiring all safety precautions to be taken to the limit of science and technology. The result was a de facto moratorium on new nuclear construction.

In contrast, although numerous reactor siting decisions have been challenged in court in France, there the court system functions as a defender of the state rather than of individual rights, and litigation is confined to legal technicalities and procedural breaches. Thus French ecologists routinely lost, and political leaders did not need to fear that their decisions could be overturned through litigation. Although France initially had nuclear policies similar to those of other European nations and a roughly equivalent protest movement, the movement had virtually no effect on policy. For there is an "intimate link between a country's political structure and the policy options available to its energy officials. The relatively pluralistic political systems of West Germany and the Netherlands (as well as Sweden and Austria) have allowed diverse groups in both countries to participate in the policy-making process and, in so doing, to place considerable constraints on the actions of government. In contrast, the French system—highly centralized and dominated by state agencies and their officials—is so structured that access to the policy-making process is quite restricted. The state as a consequence has been relatively unencumbered in pursuit of its favored energy policy objectives."⁴³

Much the same is true of Japan, only to a greater extent. Historically, the political culture has not encouraged direct citizen action in politics, and many Japanese still doubt whether "under ordinary circumstances public opinion and the activities of the citizenry will have a serious impact on their government's decisions."⁴⁴ The nation has seen student movements, New Left sects, activist unions, a large

43. Michael T. Hatch, *Politics and Nuclear Power: Energy Policy in Western Europe* (Lexington: University Press of Kentucky, 1986), pp. 191–192. Two of the best works of the 1970s on the European experience are Henry R. Nau, *National Politics and International Technology: Nuclear Reactor Development in Western Europe* (Baltimore: Johns Hopkins University Press, 1974); Peter deLeon, *Development and Diffusion of the Nuclear Power Reactor: A Comparative Analysis* (Cambridge, Mass.: Ballinger, 1979).

44. Ezra F. Vogel, *Japan's New Middle Class* (Berkeley: University of California Press, 1968), p. 97.

Socialist party, and such dramatic confrontations as the lengthy and militant Sanrizuka effort to stop the new airport in Tokyo. Nevertheless, policy making generally is not much influenced by direct input from citizens, and political scientists have often noted "the undemocratic character" of Japanese political participation.⁴⁵ The political system is characterized by "a lack of due process, . . . inadequacy of consultative mechanisms outside elite circles and the failure of local government to represent local interests."⁴⁶

Japan has a "one-and-a-half-party system" that allows domination of the government by the Liberal-Democratic party, with little prospect for the Socialists to displace them; as a result there is less incentive than in most representative democracies for elected officials to pay careful attention to the demands of interest groups. The unions have little political clout, for they have generally been associated with the toothless Socialist party. And most other interests, including business, have "by means of financial contributions established close relationships with the party in office."⁴⁷ It is true that environmental policy has changed considerably in Japan, and that environmental groups have played a role in calling attention to various problems; but there have been nothing like the public information campaigns, lobbying, and litigation characteristic of the American system to force unwilling officeholders to bend to citizens' wishes.⁴⁸ Likewise, although the Japanese judiciary has the power of judicial review and has taken an activist stance in some traditional pollution cases, "throughout its history, the Supreme Court has been far more active in reversing antigovernmental decisions made by lower courts than in challenging any important government actions."⁴⁹

45. Tadashi Fukutake, "Village Community (Buraku) in Japan and Its Democratization," in Robert J. Smith and Richard K. Beardsley, eds., *Japanese Culture: Its Development and Characteristics*, Viking Fund Publications in Anthropology, vol. 34 (Chicago: Aldine, 1962), p. 87. See also Kurt Steiner, "Popular Political Participation and Political Development in Japan: The Rural Level," in Robert E. Ward, ed., *Political Development in Modern Japan* (Princeton: Princeton University Press, 1968), p. 243.

46. David E. Apter and Nagayo Sawa, *Against the State: Politics and Social Protest in Japan* (Cambridge: Harvard University Press, 1984), p. 4.

47. Takeshi Ishida, "The Development of Interest Groups and the Pattern of Political Modernization in Japan," in Ward, *Political Development*, pp. 293-336; the quotation is from p. 325.

48. See Margaret A. McKean, *Environmental Protest and Citizens' Movements in Japan* (Berkeley: University of California Press, 1981).

49. T. J. Pempel, *Policy and Politics in Japan: Creative Conservatism* (Philadelphia: Temple University Press, 1982), p. 19.

All told, the worldwide experience with nuclear power underscores our concern with the uneasy relationship between technology and democracy. Nuclear power has been drastically slowed or stopped in most nations that have ready channels for translating citizens' demands into policy, and even in some nations that do not. Large-scale, expanding nuclear power programs remain in full swing only in political systems that make it very difficult for citizens to influence policy: France, Japan, and some of the communist and authoritarian political systems.

This is fascinating and disturbing. For if France and Japan successfully use nuclear power to reduce greatly their reliance on fossil fuels, then we must confront the possibility that popular influence in other nations has interfered with a technology that could have brought substantial benefits. On the other hand, what sort of a society is it that allows technical potentials to outweigh popular wishes? Does the relationship between complex technology and democracy have to come down to that sort of choice?

Democracy and Technology

It is worth recalling that concerns like ours about technology and democracy are not new. Indeed, almost since the reemergence of Athenian democratic ideals in seventeenth-century Europe and their transport to the American colonies, thoughtful observers have expressed concern about whether increasing reliance on technology is compatible with self-government and other important human values. Sometimes these concerns are expressed in the context of criticizing who is in control. Marx wrote that factory workers of his day were "a mere living appendage" of the machine, controlled by the capitalist class.⁵⁰ More recently, David Noble has argued that the direction of factory automation is set less by the new technology per se than by the desire of management to have greater control over the workplace.⁵¹ Of course control by "the wrong people" may also occur in governmental decision making about technology.

Early in the twentieth century many social analysts perceived inefficient use of technology as a bigger problem than nondemocratic

50. Karl Marx, *Capital*, vol. 1, 3d ed. (New York: Modern Library, 1906), p. 416.

51. David F. Noble, *Forces of Production: A Social History of Industrial Automation* (New York: Alfred A. Knopf, 1984).

control. To bring about a thoroughly ordered and mechanized society of the future would require "scientific management" by a new generation of powerful managers, according to Frederick W. Taylor.⁵² The futuristic fictions of H. G. Wells likewise portray the coming age as one requiring rule by highly trained technicians.⁵³ Thorstein Veblen shared their hope that engineers would assume a position of greater authority, but bemoaned the continuing inefficiency of the "vested interests" who owned and managed industry.⁵⁴ Other observers have been concerned about the opposite problem: too much authority for experts, too little for ordinary citizens.

The various critiques of technocracy and elitism obviously differ in most respects, but they concur in perceiving technologies as neutral tools steered for better or worse by human motives and institutions. Since the 1930s, however, a number of thoughtful social analysts have suggested that "the privileged position of an elite or ruling class is not proof that it steers the mechanism but only that it has a comfortable seat for the ride."⁵⁵ Abbott Payson Usher, Lewis Mumford, Siegfried Giedeon, Jacques Ellul, Herbert Marcuse, and others have asked whether socially organized technology may impel any group of elites to follow more or less the same course: "Under present conditions men are not at all the masters of technological change; they are its prisoners."⁵⁶ In the eyes of these social critics, technology has an inherent momentum that is very difficult to arrest.

According to a fourth perspective, "technological somnambulism" is the most accurate characterization of human relations with technology. As formulated by Langdon Winner, this idea holds that human choices indeed launch particular technological developments, but that the new endeavors seldom receive the degree of conscious, careful design necessary to satisfy the long-term needs of society.⁵⁷

52. F. W. Taylor, *The Principles of Scientific Management* (New York: Harper and Row, 1947). A recent analysis of technocracy is Andrew Massey, *Technocrats and Nuclear Politics: The Influence of Professional Experts in Policy Making* (Brookfield, Vt.: Avebury, 1988).

53. H. G. Wells, *A Modern Utopia* (Lincoln: University of Nebraska Press, 1967).

54. Thorstein Veblen, *The Engineers and the Price System* (New York: Viking, 1954).

55. Langdon Winner, *Autonomous Technology: Technics-out-of-Control as a Theme in Political Thought* (Cambridge: MIT Press, 1977), p. 41.

56. *Ibid.*, p. 55.

57. "The interesting puzzle in our times is that we so willingly sleepwalk through the process of reconstituting the conditions of human existence." *The Whale*

Moreover, human choices may be substantially constrained and distorted by a variety of cultural, organizational, political, and economic forces. Winner argues that before diffusing new technologies, governments and businesses do not ask sufficiently pointed questions about the purposes the technologies are supposed to serve, how they should be controlled, or how they are to be held to the intended purposes and not others. The result is technological drift, in which technologies seem to take on a life of their own.

Mary Shelley's story of *Frankenstein* is a forerunner of this line of thought: the story's creature was obviously the product of Victor Frankenstein's original intentions, but Frankenstein did not establish a context that allowed his creation to live a satisfactory existence. As a result, the technology behaved in unexpected ways that ended up disrupting the community while harming the creator and those around him.⁵⁸

It turns out that each of these perspectives, especially the last, explains part of the demise of American nuclear power. But we find that the travails of the industry reveal a somewhat more complicated formulation of the uneasy relationship between technology and democracy. As we read it, the story of nuclear power is more than anything else about democratic institutions at work, and the failure of these institutions to live up to some of their own standards.

Scope of the Inquiry

To reiterate, this is not a study of why the public finds nuclear power unacceptable. There are other good analyses of that question, and this book starts where the others leave off. We take it as a given that the technology is politically and economically unacceptable, and we acknowledge that the decision has been shaped in part by political elites, cognitive processes, and other forces. Our goal is to find out how the American political system failed to modify a multibillion-dollar program that was becoming politically unacceptable. By the same token, the ills of the current nuclear industry have been inten-

and the Reactor: A Search for Limits in an Age of High Technology (Chicago: University of Chicago Press, 1986), p. 10.

58. Mary Shelley, *Frankenstein, or the Modern Prometheus*, ed. James Rieger (New York: Bobbs-Merrill, 1974). For a discussion of "Frankenstein's problem" see Winner, *Autonomous Technology*, pp. 306–335.

sively studied, and we take such analyses as our starting point. We discuss regulatory, managerial, and other flaws only in passing; the main inquiry concerns why the United States developed such a flawed system and stuck with it.

To answer these questions, we have delved extensively into the history of nuclear power. But our treatment is far from comprehensive;⁵⁹ we analyze only those selected aspects of the history pertinent to our argument. For example, except when there is a direct bearing on our theme, we do not attempt to cover the short-term politics of nuclear power—activities of interest groups, bureaucratic struggles within the Atomic Energy Commission, congressional skirmishes, or the protracted legal battles that still wind through the courts—as important as these are for anyone who wants a general understanding of the subject. For although political conflict attends most important governmental endeavors, very few end up as spectacularly unacceptable as nuclear power. Likewise excluded are many of the substantive arenas of the controversy, such as the disposal of radioactive wastes, international proliferation, local siting controversies, and the question of whether nuclear power plants are “safe enough” by some objective standard.⁶⁰

This volume is also selective in that it focuses on the United States. Most of the world has imported American reactor technology, so to understand the nuclear power systems now being rejected by people in many nations one needs to focus on their American origins. As will become apparent, we believe that the world’s experience with nuclear power could have been much better had events developed differently in the nation where nuclear power originated.

59. For historical overviews see Mazuzan and Walker, *Controlling the Atom*; Richard G. Hewlett and Francis Duncan, *Atomic Shield, 1947–1952* (University Park: Pennsylvania State University Press, 1969). Three important specialized studies are Richard G. Hewlett and Francis Duncan, *Nuclear Navy, 1946–1962* (Chicago: University of Chicago Press, 1974); David Okrent, *Nuclear Reactor Safety: On the History of the Regulatory Process* (Madison: University of Wisconsin Press, 1981); Richard T. Sylves, *The Nuclear Oracles: A Political History of the General Advisory Committee of the Atomic Energy Commission, 1947–1977* (Ames: Iowa State University Press, 1987).

Many additional sources can be found in Jerry W. Mansfield, *The Nuclear Power Debate: A Guide to the Literature* (New York and London: Garland, 1984); *Nuclear America: A Historical Biography* (Santa Barbara: ABC-Clio, 1984).

60. For an extended treatment of the question “How safe is safe enough?” see Joseph G. Morone and Edward J. Woodhouse, *Averting Catastrophe: Strategies for Regulating Risky Technologies* (Berkeley: University of California Press, 1986), esp. chap. 8.

Finally, we intend this book to be as unpoliticized as possible. We have a point of view, but it is neither pronuclear nor antinuclear. We want the book to be equally relevant for partisans on either side of the issue, as well as those still forming their opinions on the subject. We are not attempting to change anyone's mind about the overall safety or desirability of nuclear power. Our aim is rather to clarify what went wrong, and how the technology could have developed differently. We believe that this retrospective inquiry leads to important insights about appropriate paths for the future, but various readers will draw somewhat different conclusions about how to apply these insights.

Our analysis of the American nuclear power system focuses on three elements: light water reactors, engineered safety, and competitive private enterprise. In part I, we review the decisions made in the early years of nuclear power that led the industry to be built around these three elements.

Chapter 2 treats the early development of civilian power reactors, from 1944 to 1953. In it we ask to what degree decision makers took safety into account when selecting potential types of reactors for development, and in comparison how heavily the Atomic Energy Commission weighed such factors as international prestige, military priorities, and economics. Our goal is to determine whether nuclear decision makers made serious errors in their early choices of reactors, which may have doomed the industry almost from the outset.

In chapter 3 we examine the beginnings of a privately owned nuclear power industry. We find a critical juncture in 1954, when Congress amended the Atomic Energy Act to encourage private enterprise to finance, construct, and operate civilian nuclear power reactors for the purpose of generating electricity. Other legislation of that period also contributed to the development of a private nuclear industry, including the Price-Anderson Act of 1957, which established liability limits for nuclear accidents. How, we ask, did the concern for a competitive nuclear power industry shape the Atomic Energy Commission's reactor development program, and what long-term effects did such concerns have on the viability of the overall enterprise?

Chapter 4 concerns the safety strategies used by the Atomic Energy Commission and later the Nuclear Regulatory Commission to

safeguard public health from potentially catastrophic accidents. Although the particulars of nuclear safety are legion, the basic strategies and tactics fall into two main categories: one aims at preventing serious problems from arising in the first place; a second is designed to alleviate such problems if they should occur in spite of the prevention efforts. The second strategy was deemphasized in the mid-1960s, and we later argue that this represented a large step toward the eventual demise of American nuclear power.

Although part I mostly retells a familiar story in a new way, part II consists largely of original analysis and interpretation. Chapter 5 deals with what we believe to be the critical juncture in the history of nuclear power: the rapid scale-up of reactor sizes in the mid-1960s, and a concomitant shift in safety strategy. We ask how this change in strategy affected the regulatory process and public opinion, and we then examine the accidents at Three Mile Island and Chernobyl in the context of the answers to these questions.

Chapter 6 is a retrospective thought experiment in which we ask the following question: What might have been done differently to change the three basic elements of the nuclear enterprise that we have described, and change them so dramatically that a far more satisfactory outcome could have been achieved? We explore what might have happened if decision makers had not selected light water reactors with engineered safety that were owned and operated by private enterprises. Is it conceivable that there might have been an altogether different approach that would be acceptable to a large majority of the public?

We reflect in chapter 7 on how the nuclear power experience affects the prospects for intelligent, democratic control of technology, and our understanding of the obstacles to such control.⁶¹ Among other issues, we discuss the importance of mounting political debates before technological momentum rigidifies options into a Hobson's

61. We use the term *democracy* for convenience; *polyarchy*, rule by many, would be more accurate. And we do not mean to suggest that representative systems of government offer their citizens anywhere near the degree of popular control over social outcomes that may someday be achievable in large, heterogeneous societies. See Robert A. Dahl and Charles E. Lindblom, *Politics, Economics, and Welfare* (Chicago: University of Chicago Press, 1976); Charles E. Lindblom, *Politics and Markets* (New York: Basic Books, 1977); Robert A. Dahl, *A Preface to Economic Democracy* (Berkeley: University of California Press, 1985).

choice. Altogether, we argue that despite surface appearances to the contrary, technology and democracy are in the end compatible.

In chapter 8 we ask where energy policy should go from here. The path now being taken by the United States and many other nations is essentially to phase out civilian nuclear power. Is this the sensible strategy? Or are the problems with fossil fuels—particularly climate changes from the greenhouse effect—sufficiently severe to warrant reappraisal of the nuclear option? If so, what strategy would combine environmental preservation, technical feasibility, financial prudence, and widespread acceptability?

Some readers may wish to begin with the appendix, which offers a brief introduction to nuclear power technology. Although the complete technical details obviously are beyond the reach of nonexperts, a layman's understanding of the subject can be obtained in less than an hour. Perhaps the most important thing to know about nuclear technology is that there are dozens of ways to design nuclear reactors, and a growing number of nuclear technologists believe it is possible to construct reactors invulnerable to catastrophic accidents.⁶² Readers who understand this will be in a better position to follow our analysis of why nuclear decision makers in the United States shaped the technology and safety strategies as they did. Even those who know almost nothing about nuclear power should find the material in the appendix easy to understand.

What Can Be Gained?

Those who confidently prescribe what should be done about the future of nuclear power have an implicit model of what is wrong or right with it. We are skeptical that the mental models now in widespread use are very good ones. Historians point out that subsequent generations typically have a much better vantage point from which to appraise historical trends than did the generation most closely involved. Instant history is rarely good history, because it lacks perspective. In our judgment, the nuclear power era is just entering the stage where systematic appraisal stands a reasonable chance of clear-sighted evaluation. Because scholars and other commentators to date have been forced to use the only lenses available to them—close-up ones—they have inevitably overemphasized some pieces of the ex-

62. A thoughtful exposition of this viewpoint can be found in Alvin M. Weinberg et al., *The Second Nuclear Era: A New Start for Nuclear Power* (New York: Praeger, 1985).

perience, and underemphasized or neglected others. As a result, we need to be somewhat cautious about the explanations now available about the problems of the technology, and open to the possibility that the perspective now being gained will lead to fundamental revisions in the way many of us look at the nuclear power experience.

If such learning indeed occurs, will it do any good, given that so many people already have their minds made up on the subject? Opinions do get reexamined as circumstances change. To the surprise of almost everyone, atmospheric warming and climatic change became a common topic of conversation and press coverage, partly as a result of record-breaking heat in summer 1988.⁶³ If this leads to a political judgment that coal is too dangerous to be the primary fuel for generating electricity, and other options prove inadequate, nuclear power may again come under active consideration. Unhappily, decisions may again be made clumsily, since many societies have failed to learn from previous mistakes. For the painful and costly experience with nuclear power over the last forty years to teach us, we need to figure out what the lessons are. Partisans may then be in a position to apply the lessons intelligently from their disparate points of view. If nuclear power is to be discontinued, this should be based on a clear-eyed assessment of our experience through the 1980s. If nuclear power is to win a second chance, surely we ought to know what to avoid and how to do better. The purpose of this book is to contribute to such scrutiny.

63. Among many other such articles see John Noble Wilford, "His Bold Statement Transforms the Debate on Greenhouse Effect," *New York Times*, August 23, 1988, sec. C, p. 4; Matthew L. Wald, "Fighting the Greenhouse Effect," *New York Times*, August 28, 1988, sec. 3, p. 1.

PART I

History

CHAPTER TWO

Origins of the Light Water Reactor

The United States has invested more than \$200 billion in an industry that is psychologically unacceptable to a majority of citizens, politically unacceptable to most elected officials, and economically unacceptable to utility companies. Was this inevitable, or did nuclear decision makers commit fundamental errors? One possibility explored throughout this volume is that nuclear power per se might have been acceptable in some form, but that the wrong type of reactor was chosen.

The origins of the choice go back to the mid-1940s, when development began on the first civilian reactors. From among more than a hundred potential types of nuclear reactor (see Appendix), one or more had to be chosen for sustained development. There was no nuclear power industry at this point, so there were few economic limitations on the choices. Because the technology was brand-new, ingrained technical traditions and professional habits were not a major constraint. International competition was not an immediate concern. And there was no Nuclear Regulatory Commission to specify procedures that had to be followed for safety.¹

1. The Nuclear Regulatory Commission's predecessor was the Atomic Energy Commission (AEC), established by the Atomic Energy Act of 1946. The Act gave control over atomic energy to a civilian authority (a five-person commission), which was a matter of significant dispute in spring and summer 1946. According to the act, the AEC's principal function was to develop atomic energy for military purposes. A second,

So reactor developers were starting with a relatively free slate. How did they proceed? Did they attempt first and foremost to design reactors suited for widespread, long-term use in society? We show that they did not; more immediate priorities governed early decision making.

The Breeder Reactors

The first nuclear power reactors were originally chosen at national laboratories, which had been established for wartime research. Even before the war ended, as the atomic bomb project shifted from research to production, scientists at these labs began to turn to new areas of research in atomic energy, including the development of reactors for civilian use.

The most important constraint facing them was a perceived shortage of uranium. There had been little need to prospect for uranium before the war, so there were few verified deposits and almost no data for estimating the total resource base. During the war proven worldwide uranium reserves accessible to the United States were estimated to be about 6,000 tons, and this was fast being depleted by the Manhattan Project. To put this figure in perspective, a single reactor of the type used by American utilities in the 1980s requires about 4,000 tons of uranium over a thirty-year lifetime. American uranium reserves are now estimated to be several million tons, with worldwide reserves considerably higher.²

less important function was to develop it for peaceful purposes.

The AEC took over operation of the organization formed in the wartime effort to develop the atomic bomb (the Manhattan Project). The most significant components of this organization were several large government research and development facilities known as "national labs."

The act of 1946 also created a unified committee of the House and Senate to oversee the AEC. As we shall see, the Joint Committee on Atomic Energy played a powerful role in the first half of the nuclear age.

See Richard G. Hewlett and Francis Duncan, *Atomic Shield, 1947-1952* (University Park: Pennsylvania State University Press, 1969); George T. Mazuzan and J. Samuel Walker, *Controlling the Atom: The Beginnings of Nuclear Regulation, 1946-62* (Berkeley: University of California Press, 1984).

2. For a discussion of early uranium estimates see Richard G. Hewlett and O. E. Anderson, *The New World* (University Park: Pennsylvania State University Press, 1962), pp. 285, 292; more recent estimates and their shortcomings are analyzed in Nuclear Energy Policy Study Group, *Nuclear Power: Issues and Choices* (Cambridge, Mass.: Ballinger, 1977), pp. 71-94. See also R. M. Williams, "Prospects and Concepts," in Leonard G. Brooks and Homa Motamen, eds., *The Economics of Nuclear Energy* (London and New York: Chapman and Hall, 1984), pp. 116-144, esp. pp. 136-142.

But the perceived scarcity of uranium during the mid-1940s strongly influenced the scientists working on peaceful applications of atomic energy. They believed that a shortage of uranium could prevent nuclear energy from becoming a practical source of power, unless they developed breeder reactors, which produce at least as much fissionable material as they burn (see Appendix for further details on these technical points and others).³ Conventional, nonbreeding reactors would waste most of the very limited supply of uranium, because they can convert to usable energy no more than 3.5 percent of the uranium they burn. The problem was not simply to develop a reactor, but to develop a breeder reactor.

As outlined in the Appendix, breeding depends on the number of neutrons released with each fission, and this number varies substantially in different kinds of reactor, depending on the type of fuel used and the speed of the neutrons. Conventional reactors now used by utility companies cannot breed, because they release too few neutrons. Nuclear scientists understood this by 1944, and they recognized that fast neutron reactors fueled with plutonium would have the most neutrons available for breeding. Two other types might have enough neutrons: intermediate-speed neutron reactors with plutonium fuel, and slow neutron reactors fueled with uranium-233.⁴

In 1944–45 scientists had not yet established whether the theoretical notions about breeding would actually prove feasible. Even after several years of research, the director of the breeder program at Argonne National Laboratory (ANL) reported in 1947 that the chances for breeding seemed “marginal at best.”⁵ Given this uncertainty, the overriding concern was to demonstrate that breeding was indeed feasible, so ANL began developing a fast neutron reactor fueled with plutonium, which offered the most neutrons available for breeding and therefore the best prospects for a practical breeder reactor.⁶

Meanwhile, scientists at Oak Ridge National Lab (ORNL) began

3. Richard G. Hewlett, “The Experimental Breeder Reactor No. 1” (unpublished paper, U.S. Department of Energy, Historian’s Office), pp. 13–14; Hewlett and Duncan, *Atomic Shield*, pp. 29, 98.

4. Breeding can also occur when a fertile thorium atom decays into a fissile uranium-233 atom.

5. Hewlett and Duncan, *Atomic Shield*, p. 29.

6. Enrico Fermi and others actually began to work on the reactor during the war while they were still at the Metallurgical Lab of the University of Chicago. See Hewlett, “Experimental Breeder Reactor,” pp. 12–16.

to work on a slow neutron breeder reactor, even though it had fewer available neutrons than the fast breeder. According to Alvin Weinberg, the leading proponent of this type of reactor, scientists at ORNL preferred the slow neutron reactor in part because they believed it would require less complicated engineering.⁷ Further, the particular type of reactor they chose, the homogeneous breeder, would waste fewer neutrons than other slow neutron reactors (see Appendix). Fundamental technical problems quickly emerged, however, and by late 1945 scientists decided that the attempt to build a homogeneous breeder was premature. As a result, ORNL turned to more basic research on homogeneous reactors.⁸ By 1949–50 this evolved into development of a small-scale homogeneous reactor that was not a breeder.⁹

Knolls Atomic Power Lab (KAPL) was established in 1946 by General Electric under a government contract to do research and development in atomic energy. Scientists at KAPL decided to develop an intermediate-speed breeder, the only known type of breeder not being explored by one of the other labs.¹⁰ Although the fast breeder was attractive to KAPL's scientists, it would have been difficult to justify a second fast reactor development program given the scarcity of uranium and scientific personnel at the time. Also, the intermediate reactor had an inherent structural advantage over the fast breeder: its core would be larger, making it easier to build and control, as well as a more efficient power producer. Another advantage, considered very important at the time because of the perceived scarcity of uranium, was that it would require a smaller fuel inventory than the fast reactor. As KAPL scientists recognized, the disadvantage of the intermediate

7. Alvin M. Weinberg, director of the Institute for Energy Analysis, Oak Ridge, Tenn., telephone interview with Joseph G. Morone, December 2, 1980.

8. The worst problem was the formation of bubbles in the homogeneous solution. The bubbles made the reactor difficult to control. See J. Lane, H. McPherson, and F. Maslen, *Fluid Fuel Reactors* (Reading, Mass.: Addison-Wesley, 1958), p. 7.

9. The AEC attempted to reorganize the reactor development program in 1947–48 in a way that would have cut Oak Ridge out of most work and probably scrapped the homogeneous reactor effort, but Weinberg lobbied persistently and effectively, successfully claiming that Oak Ridge's main mission, neutron research, required a new research reactor. See *ibid.*; Hewlett and Duncan, *Atomic Shield*, pp. 209, 219.

10. H. Stevens, interview with Joseph G. Morone, Knolls Atomic Power Lab, January 1980; Henry Hurwitz, interview with Joseph G. Morone, General Electric Company Corporate Research and Development Center, Schenectady, N.Y., January 1980. Both Stevens and Hurwitz participated in the decision process described here.

reactor was that the number of neutrons available in it for breeding was still uncertain. Wartime research had studied only fast neutrons, necessary for bombs.¹¹

In sum, technical factors almost completely determined the early reactor choices. By far the dominant consideration was the perceived need for breeding, arising out of the apparent scarcity of uranium. Scientists and engineers at ANL selected the fast breeder because it was the most likely to breed; considerations of safety did not influence the choice. Thus, for example, scientists opted for liquid metal coolant because it removes heat more efficiently than other coolants.¹² Yet sodium explodes on contact with water, through which the coolant would have to pass (in pipes) in the steam generator. This very substantial safety issue was considered later in reactor development, but apparently neither it nor any other safety consideration influenced the fast breeder's initial selection.¹³

The same applies to the selection of the homogeneous reactor. In the words of its leading proponent, the relative safety of the possible breeders was not a "dominant consideration at the time."¹⁴ Instead, scientists at Oak Ridge believed that homogeneous reactors would in the long run require the least complex engineering, and that breeding would be more likely in a homogeneous reactor than in another type of slow breeder.

KAPL's intermediate breeder likewise originated more from practical necessities and the inherent attractions of intermediate reactors than from safety considerations. As one of the physicists who participated in the project put it, "there was very little 'soul searching' about the ultimate merits of the IBR [intermediate breeder reactor]. We needed a reactor project, and the IBR provided an obvious opportunity for one."¹⁵

That safety was not an explicit consideration in selecting reactors for development does not mean that the scientists were unconcerned

11. Hewlett, "Experimental Breeder Reactor," p. 21.

12. *Ibid.*, pp. 19, 26–27; Hurwitz, interview with Morone.

13. Henry Hurwitz, interview with Joseph G. Morone, General Electric Company Research and Development Center, Schenectady, N.Y., November 19, 1980. Hurwitz described a lecture given at Los Alamos (one of the other labs) in fall 1945 by Fermi, the most important and influential physicist at Argonne. In his lecture Fermi traced the evolution of ANL's breeder reactor.

14. Weinberg, interview with Morone.

15. Hurwitz, interview with Morone, January 1980.

about the potential for serious accidents. Even in these early days, before any reactor type was seriously considered for development it went through a period of preliminary research.¹⁶ One question that had to be answered was whether the safety-related problems inherent in the proposed reactor concept could theoretically be overcome.

For instance, one of the issues in the early investigations of ANL's fast breeder was whether in abnormal or emergency conditions the rate of fission could be kept under control. Because the neutrons would not be slowed down, there would be a smaller margin for error. The scientists at ANL had to demonstrate that in theory the rate of fission could be controlled. Likewise, they had to satisfy themselves that the particular coolant they had chosen, liquid metal, theoretically could be kept separate from the water in the steam generator.¹⁷

The selection process for the early civilian reactors did take safety into account to some extent, but clearly safety was not the driving force in the choices. Scientists at the various labs were not seriously analyzing the implications of using such reactors throughout society. Pioneering a vague, ill-formed vision of a future technology, they were struggling with vast unknowns and a serious uranium shortage. The desire to achieve breeding overshadowed all other considerations.

The Submarine Reactors

The reactor that encountered problems at Three Mile Island was a descendant of a pressurized water reactor developed in the late 1940s and early 1950s to power a submarine. That reactor's peculiar origins are the next step in the evolution of nuclear power technology.

The idea of powering submarines with nuclear energy had been gaining adherents in the navy since shortly after the discovery of atomic fission in 1938. A report by the Submarine Officers' Conference in 1947 requested that the navy "design and develop nuclear power plants for eventual installation in submarines to give unlimited submerged endurance at high speed."¹⁸ The conference recom-

16. See for example W. K. Davis and U. N. Staebler, "Highlights of Nuclear Power Development in the United States," *Proceedings of the Second International Conference on the Peaceful Uses of Atomic Energy*, vol. 1 (Geneva: United Nations, 1958), p. 82.

17. Hurwitz, interview with Morone, January 1980.

18. Quoted in Norman Polmar and Thomas B. Allen, *Rickover* (New York: Simon and Schuster, 1982), p. 137. On the period 1938–46 see pp. 118–136.

mended that at least two of the navy's first postwar submarines be propelled by the new technology. The chief of naval operations, who had requested the report, quickly endorsed it.

Although the AEC was not opposed to a navy reactor, it did not consider it a high priority, because the new organization had numerous other issues to face in its first several years of operation. To push its policies, the navy used a tactic that has since become familiar in military budget battles—pointing to the Soviet threat: “Naval Intelligence estimated that the Soviet Navy could be building a fleet of modern submarines to sever the United States from Europe. If the Soviets attained the maximum German wartime production rate of twenty-five submarines per month, the Soviet submarine fleet could reach a thousand undersea craft in just over three years.”¹⁹ Because American plans called for only a few new submarines each year, Adm. Earle W. Mills of the navy's Bureau of Ships told the AEC in June 1948 that subs propelled by nuclear power were necessary to help redress the predicted imbalance.

When the AEC did not respond to the navy's proposals with a specific commitment, Mills appointed Capt. Hyman Rickover as the navy's liaison to the AEC; soon Rickover also became the head of a new Nuclear Power Branch within the Bureau of Ships. According to AEC historians, “The task needed the kind of hard-headed, even ruthless, direction which he knew Rickover would give it. . . . Mills could guess that once he gave Rickover a free hand, he would outwork, outmaneuver, and outfight the Commission, its laboratories, and the Navy. He would threaten, cajole, and even insult those who stood in his way.”²⁰ In early 1949 the AEC formed a Division of Reactor Development, with a Naval Reactors Branch led by Rickover and relying primarily on his nuclear staff from the Bureau of Ships: “This dual-agency situation was ideal for Rickover, permitting him immediate and direct access to both organizations, while he could take advantage of either agency's letterhead to bring pressure on the other. Further, Rickover had access to both AEC and Navy field activities (laboratories

19. Polmar and Allen, *Rickover*, p. 142. The Soviet nuclear submarine fleet has never come close to that number, of course. The number of American nuclear submarines is approximately one hundred.

20. Richard G. Hewlett and Francis Duncan, *Nuclear Navy, 1946–1962* (Chicago: University of Chicago Press, 1974), pp. 75, 76.

and shipyards) and their industrial contractors.”²¹ From that point the naval reactor program moved ahead rapidly.

Two major considerations dominated Rickover's selection of a submarine reactor. First, it obviously had to be relatively compact.²² Second, it had to be developed quickly. The submarine project had been proposed and justified as a response to growing Soviet aggression and advances in Soviet submarine capabilities. It was therefore directed at the immediate needs of national defense, not the long-term advancement of reactor technology.²³

These two requirements eliminated most reactor types from consideration. Advanced types such as the fast breeder and homogeneous reactors could not be developed quickly enough. Reactors moderated by heavy water or graphite, although more familiar than any other reactor types because they were used to produce bomb-grade nuclear material during the war, were too large to be used in submarines. This left pressurized light water reactors and several types of beryllium-moderated reactors as the only options.²⁴

Ordinary (light) water had initially been rejected for use in reactors because it had serious drawbacks as a moderator and coolant. Early reactors had to be fueled with natural uranium, and ordinary water absorbed too many neutrons to keep the chain reaction going in a natural uranium reactor.²⁵ Once enriched uranium became available after the war, however, it became possible to use light water as the moderator.

Water also became more attractive as a coolant. Scientists had originally assumed that a reactor would become unstable if the water in the core were allowed to boil; reactors therefore had to be operated

21. Polmar and Allen, *Rickover*, p. 143.

22. On this point see U.S. Congress, Joint Committee on Atomic Energy, *Hearings on Atomic Power Development and Private Enterprise*, 83d Cong., 1st sess., 1953, p. 241.

23. Hewlett and Duncan, *Nuclear Navy*, pp. 71–73, 85–86; Hewlett and Duncan, *Atomic Shield*, pp. 190–193.

24. Hewlett and Duncan, *Nuclear Navy*, p. 63.

25. In natural uranium only 0.7 percent of the nuclei are fissionable. In a reactor fueled by natural uranium there is therefore a much higher probability that the neutrons released in fission will be absorbed by nonfissile U-238 nuclei than by fissile U-235 nuclei. If in addition a neutron-absorbing material such as light water is used as moderator, the chances of a chain reaction are further reduced. Thus only graphite and heavy water, both of which have a relatively low affinity for neutrons, could be used as moderators as long as natural uranium was used as fuel.

at temperatures below water's boiling point. This was unattractive because it limited the amount of power that could be produced. In 1946 scientists at Oak Ridge suggested that this limitation could be overcome by pressurizing the water. Because the boiling point increases with pressure, pressurization would allow operation of water reactors at higher, more useful temperatures.²⁶

These two developments did not make water seem superior to other moderators and coolants: it still absorbed more neutrons than other moderators and was a relatively inefficient cooling agent. But now light water reactors could at least be included among possible reactor types. And water obviously had one important advantage over the other moderators and coolants: it was a familiar material that had been used extensively in industrial applications. There were few unknowns associated with its use, the problems that did arise from it were well understood, and it was cheap and abundant. Light water reactors might not be as economical in the long run as other types, nor as fuel-efficient, but because water was so familiar they would be easier to develop.²⁷

Preliminary studies of the possible submarine reactors suggested that although there were problems facing the pressurized light water reactor (PWR), they appeared surmountable; in any case the difficulties were less extensive than those likely to arise in the development of the alternative reactor types.²⁸ The PWR could be built in less time and with less difficulty than any of the others, and for this reason Rickover selected a PWR for the submarine program.²⁹

A Second Submarine Reactor

Rickover believed that the only way to determine if a particular reactor type could be made into a useful, reliable machine was actually to develop, construct, and operate it; design and experimental studies would not provide the answers.³⁰ But development, construc-

26. Hewlett and Duncan, *Atomic Shield*, p. 70.

27. *Ibid.*

28. The alternatives were a helium-cooled, beryllium-moderated reactor, a sodium-cooled, beryllium-moderated reactor, and a bismuthalloy-cooled, beryllium-moderated reactor. See Hewlett and Duncan, *Atomic Shield*, p. 212; Hewlett and Duncan, *Nuclear Navy*, pp. 94–96.

29. *Ibid.*, pp. 101–102. See also C. Allardice and E. Trapnell, *The Atomic Energy Commission* (New York: Praeger, 1974), p. 107.

30. Hewlett and Duncan, *Nuclear Navy*, p. 69.

tion, and extended operation of a reactor could take as much as ten years (for a reactor with the technological base already established). If the reactor proved unreliable at the end of that period, a new reactor would have to be selected and developed. This would be too long for a project intended for near-term military tasks. Rickover responded to this dilemma by calling for simultaneous development of at least two reactor types.³¹ If one of the reactors proved unreliable after the period required to make it operational, another would still be available to meet the military's perceived requirements.³²

The disadvantage of simultaneous development projects is that they require large expenditures of resources, and skilled manpower and other resources were extremely scarce in the field of atomic energy in the late 1940s. A second submarine reactor project could be undertaken only by canceling one of the ongoing reactor projects and transferring its resources and manpower to the submarine program. This is what Rickover proposed. For more than two years he tried to persuade the Atomic Energy Commission to convert KAPL's intermediate breeder reactor into a submarine reactor of the same basic type.³³ Initially the AEC resisted this suggestion and Rickover was forced to proceed with only the pressurized water reactor.

In 1949, however, scientists at KAPL discovered that not enough neutrons were available in an intermediate reactor for breeding. Their reactor could be made to breed only if it were turned into a fast reactor, and they recommended that this be done. But the AEC rejected the idea, in part because Argonne was already working on a fast breeder reactor. In addition, by 1949 uranium was proving much more abundant than previously believed, so breeding was no longer considered vital. At the same time, growing cold war tensions were leading the AEC to emphasize military projects.

For these reasons the AEC decided to convert the KAPL project

31. *Ibid.*

32. Simultaneous development was first undertaken during World War II in the Manhattan Project. Several methods were available for developing fissionable material for bombs, but decision makers were uncertain about which could be developed most quickly, and speed was considered essential. The dilemma was similar to Rickover's: if the wrong approach were selected, by the time the mistake was discovered it could be too late to begin anew with a different method. The Manhattan Project's decision makers resolved the dilemma the same way Rickover did: by developing several approaches simultaneously.

33. See Hewlett and Duncan, *Nuclear Navy*, pp. 69ff.

into a second submarine reactor. This was to be essentially of the same type that KAPL had been developing all along: an intermediate-speed neutron, sodium-cooled reactor. Only the reactor's purpose was different: it was to propel a submarine rather than produce electricity and breed plutonium. Thus by 1949 Rickover had his simultaneous projects.³⁴

Like the early breeder reactors, the submarine reactors were chosen for reasons specific to their context. Rickover and his associates made their choices in response to short-term, geopolitical pressures. They wanted to develop working nuclear submarines as quickly as possible to meet the perceived Soviet threat. This single consideration drove their choices, just as the imperative to develop a breeder reactor drove the initial reactor decisions in the mid-1940s. The decision makers in the nuclear submarine program certainly did not worry about whether the reactor types they were choosing were particularly safe or well suited to widespread use in society. It probably never occurred to them that the choices they were making would heavily influence the later evolution of a civilian nuclear industry. Nor is it clear in hindsight how they might have been expected to make such calculations.

The Civilian Reactor Development Program of 1952

With the intensification of the cold war in the late 1940s, the Atomic Energy Commission directed the bulk of its resources to military reactors. These included reactors to produce plutonium for nuclear weapons, as well as the two submarine projects. No power-producing reactor projects were initiated during the period. Meanwhile, small versions of the fast breeder and homogeneous reactors had been put into operation, and the submarine reactors were well under way.

By the early 1950s the emphasis on military applications was being offset by a growing sentiment to accelerate development of atomic energy for peaceful purposes. Several members of Congress were proposing that a large power reactor be built, industry was becoming interested in the prospects for commercial nuclear power, and leading decision makers were calling for increased private partici-

34. Hewlett and Duncan, *Atomic Shield*, pp. 421–423.

pation. Thus when the AEC turned to the formulation of plans for its second generation of reactors, a distinct and important objective was the development of reactors for civilian purposes.

In 1952 the AEC's Reactor Development Division devised a new civilian reactor development program. One of the driving considerations at the time was the formidable uncertainty still associated with the technology. As the division's director described it: "We are unable, at the present time, merely by making paper studies and analyses and so on to pick which particular reactor design is going to be the winner. It is like guessing whether the 1955 Chevrolet or the Ford is going to be the best automobile. It is pretty hard to tell in advance."³⁵

Faced with such uncertainty, the AEC devised a strategy that came to be a hallmark of reactor development in the 1950s. Rather than gamble on the selection of a single reactor type, and face the possibility that a serious technical obstacle would emerge sometime during the decade that it would take to develop it, the AEC would hedge its bets by developing several distinct reactor types simultaneously. Unless serious problems emerged, development of each type would proceed at least to the construction and operation of early prototypes. Then, once experience had been gained and uncertainty reduced, a choice among the types could be made. As the AEC's general manager noted several years later, reactor development "is like breeding horses to get a Kentucky Derby winner. You train them and when it comes time for the race, you stick [with] the one that has the best chance to win. But you don't decide at the time you breed a stallion to a mare that it is going to be a derby winner. You hope you have one. You have to develop several of them."³⁶

In hindsight, this was a pivotal point in the evolution of nuclear power. Decision makers were explicitly considering alternatives for the civilian use of nuclear power, and at this point in the history of reactor development safety and future public acceptability might reasonably have been expected to enter as major considerations. But

35. Joint Committee on Atomic Energy, *Hearings on Atomic Power Development and Private Enterprise*, p. 23. See also U.S. Atomic Energy Commission, Memo 649/1, May 1953 (unpublished memorandum, U.S. Department of Energy, Historian's Office), p. 3.

36. U.S. Congress, Joint Committee on Atomic Energy, *Hearings on Development, Growth, and State of the Atomic Energy Industry*, pt. 1, 84th Cong., 1st sess., 1955, p. 149.

there is no evidence that they did. There are no records of sustained deliberation over safety and acceptability in the available documents of the archives of the AEC; nor does the detailed account by the AEC's chief historian indicate any search in the 1950s for reactors that would be particularly safe or well suited to widespread use in society.³⁷

Instead, it appears that the Reactor Development Division based its "new" program on the reactor types already under active development in 1951.³⁸ This is how Walter Zinn, then the director of the Argonne National Lab, perceived the selection process. Some years later he told the congressional joint committee:

You must confess [that the development program of 1952] did not represent a considered judgment on the part of the Commission that that was all in the way of reactor types that could be profitably exploited at the time.

What it was, was an identification of types then under development in Commission Laboratories, and labeling of them as the 5-year program. I think if you look at the whole group of reactor types, you will see there are precisely those types that the technicians in the Government laboratory happen to at that time have chosen as the ones to be working on, not as the ones which among all possible ones should be then exploited for commercial development.³⁹

Nor did the AEC do much winnowing. It kept the two reactors that incorporated the most advanced technology—the homogeneous reactor and the liquid metal fast breeder—because its staff believed that these had the potential to achieve the lowest costs of power production.⁴⁰ The other three reactor types did not appear to have potential for very low costs, but they could perhaps develop into economically viable power producers and would be easier and

37. See Hewlett and Duncan, *Atomic Shield*, for the history until December 1952.

38. It was also supporting basic research on other types. Considerably more research on these others would be required before small versions could actually be built.

39. U.S. Congress, Joint Committee on Atomic Energy, *Accelerating the Civilian Reactor Development*, 84th Cong., 2d sess., 1956, p. 409.

40. See U.S. Atomic Energy Commission, Memo 649/1; Hewlett and Duncan, *Atomic Shield*, pp. 517–518.

quicker to develop.⁴¹ Therefore the Reactor Development Division decided to continue development of the sodium-graphite reactor and either the light or heavy water reactors.⁴² The apparent basis of the choice was that given limited funds, less information would be lost by dropping one water reactor than by abandoning the sodium-graphite type. Many of the lessons learned in developing one type of water reactor would be applicable to the other.⁴³

But it was not clear which water reactor was superior; each had advantages and disadvantages, proponents and critics. Ultimately the staff selected the pressurized light water reactor. At the time the AEC was already developing a PWR for use in an aircraft carrier (in addition to the submarine project). The specifications and requirements for a reactor intended to propel a large surface vessel are similar to those for a reactor intended to produce power. Much of the design work being performed for the pressurized light water carrier reactor could therefore be applied to the construction of a pressurized light water power reactor; this would save time and money. For this reason, rather than because of any judgments about relative safety, economics, or overall future prospects, the staff chose the light water reactor over the heavy water type.⁴⁴

In sum, civilian reactor development in the early 1950s was concentrated on four types of reactors. Technical and economic considerations dominated the choice of all four (table 2.1).

The Shippingport Reactor

Early in 1953 the Eisenhower administration, which had been newly elected, ordered extensive cuts throughout the federal budget. The AEC was forced temporarily to cancel its four reactor projects, as well as stop development efforts on a nuclear airplane. The administration

41. See for example U.S. Congress, Joint Committee on Atomic Energy, Subcommittee on Research and Development, *Report of the Subcommittee on Research and Development on the Five-Year Reactor Development Program Proposed by the AEC*, 83d Cong., 2d sess., March 1954.

42. See Atomic Energy Commission, Memo 649/1; Hewlett and Duncan, *Atomic Shield*, pp. 517–518.

43. Atomic Energy Commission, Memo 649/1.

44. *Ibid.*, p. 2; Hewlett and Duncan, *Atomic Shield*, pp. 517–518. The heavy water reactor had originally been selected because it was well suited to plutonium production.

Table 2.1 The Reactor Development Program of 1952

Reactor Type	Main Reasons Selected
Fast breeder	Most likely to breed; potential low-cost power producer.
Homogeneous	Believed to be technically simpler than fast breeder; most likely to breed among slow types; potential low-cost power producer.
Pressurized water	Could be developed quickly; would fit a submarine; applicable both to aircraft carrier and to commercial use.
Sodium-Graphite	Sodium a good coolant; different technology, so AEC would learn from it.

also proposed to cancel the navy’s aircraft carrier reactor project, for which the irrepressible Hyman Rickover was the director and chief advocate. To save his project, Rickover turned to allies on the Atomic Energy Commission and the Joint Committee on Atomic Energy, who devised a plan that would both save the project and provide the sort of reactor program they wanted. They proposed to continue construction of Rickover’s light water reactor, but to modify it from a carrier reactor to a power producer.⁴⁵ The reactor was to be built at Shippingport, Pennsylvania, and thus became known as the Shippingport reactor.

The idea had strong political appeal, satisfying the growing sentiment in Congress and elsewhere for more rapid development of atomic energy for civilian purposes. The only group in opposition was the AEC’s Reactor Development Division, for the project directly contravened its strategy. The division advocated patient exploration of technologically sophisticated reactors (some might say exotic reactors). Such reactors would require years of experimentation, research, and development before even prototypes could be built. But the division did not think that less technologically sophisticated reactors (for example, pressurized water reactors) had reasonable prospects for economic viability.⁴⁶

45. See Hewlett and Duncan, *Nuclear Navy*, pp. 228–238; Thomas E. Murray, *Nuclear Power for War and Peace* (New York: World, 1960), pp. 157–160.

46. See for example *ibid.*; Atomic Energy Commission, Memo 649/1; Subcommittee on Research and Development, *Report on the Five Year Program*. For further detail on the Shippingport reactor see Robert L. Loftness, *Nuclear Power Plants* (New York: D. Van Nostrand, 1964), pp. 92–106.

Key AEC commissioners and legislators disagreed, preferring the strategy employed by Rickover in the submarine project: choose the reactor type that seems easiest to develop. Instead of a reactor with great long-term promise, proponents of this strategy favored the most feasible reactors, ones with an established technical base. These could begin with relatively large, power-producing prototypes rather than the small, simple, experimental versions required by the division's strategy. In the view of Commissioner Thomas Murray, proponents of the division's strategy were perfectionists:

They preferred to continue research and development efforts on a modest basis and wait to build a big unit until they were sure that the power produced by it could compete in cost with conventional power. I was in favor then, and am now, of constructing full-scale units designed according to technology already known or within reasonable reach of the engineers' grasp. I was persuaded that we had much to learn and that we could learn only by building and operating many large scale reactors. . . . One does not obtain . . . answers from a 10,000 Kilowatt prototype reactor. We cannot, for example, enlarge it to a 100,000 Kilowatt commercial model merely by making all the necessary multiplications. A big reactor differs from a small reactor qualitatively as well as quantitatively. . . . That is why I have constantly reiterated the need for a broad construction program of large reactors of different types.⁴⁷

Murray and his allies prevailed. Under Rickover's direction, a relatively unsophisticated pressurized water reactor was constructed, on time and under budget. It produced power satisfactorily from 1957, and provided substantial impetus for the commercial application of light water nuclear technology.

Even as nuclear power neared commercial viability, however, the critical choices still followed the by now familiar pattern. The Shippingport reactor was selected not because it seemed particularly safe or well suited to society, but because it happened to satisfy the existing configuration of political interests and near-term technological opportunities. The Eisenhower administration sought to reduce the federal budget; Rickover wanted to save his carrier reactor project; the Joint Committee on Atomic Energy believed that preserving the

47. Murray, *Nuclear Power*, p. 160.

country's international prestige required early demonstration of a power-producing reactor; and some of the commissioners wanted construction of a large-scale reactor rather than "perfectionist" experiments. Conversion of the carrier reactor project provided an opportunity that satisfied them all.

Four major sets of decisions highlighted nuclear power's first decade: those associated with the breeder reactors, the submarine reactors, the first civilian reactor development program, and the Shippingport demonstration reactor. These choices were made by diverse actors operating in various contexts at different times, and pursuing a variety of purposes. The locus of decision making during this period shifted away from the national laboratories and was centered in the Atomic Energy Commission. Major decision makers included the director of reactor development and his staff, the AEC's general manager, and the five members of the AEC. The Joint Committee on Atomic Energy also was becoming a prominent and insistent participant in the process. But from our vantage point a similarity stands out: all the decisions were made in response to short-term pressures and influences defined by time and context.

The perceived need for breeder reactors dominated the first wave of reactor decisions; the result was that nuclear decision makers at the national labs chose types of reactors on the basis of the number of neutrons available for breeding. Compactness and feasibility dominated the second wave of decisions pertaining to submarine reactors. The third set of choices, associated with the reactor development program of 1952, turned out to be merely a continuation of the efforts already under way, and so was mostly a product of the same forces as the previous choices. Finally, the decision to build the Shippingport reactor was the combined product of a clever response to budgetary constraints, Rickover's commitment to build a reactor useful for aircraft carriers, and the desire of some members of the AEC and Joint Committee on Atomic Energy to construct quickly a relatively large, power-producing reactor.

What are we to make in hindsight of these early decisions? Given their values and the knowledge then available, nuclear decision makers appear to have been responding reasonably to the pressures and challenges before them. For example, it is hard to imagine a set of arguments that could have led the national laboratories to select re-

actors other than the breeders in the mid-1940s. And it is hard to imagine them selecting a relatively exotic reactor type to meet what at the time was considered an urgent need for a nuclear navy. So even in retrospect, the various decisions appear to have been reasonable responses to the problems and constraints of their time.

The problem with these decisions is that they turned out to have had an enormous impact on the shape that nuclear power eventually took. Were the decisions reasonable from this longer-term perspective? Did nuclear policy makers adequately consider whether the reactors they were selecting were well suited to widespread use in society? Clearly they did not. Safety was not a significant consideration in the choice of reactors for development in the first decade of American nuclear power. We shall see that a great deal of attention was eventually paid to safety, but only *after* a particular reactor was selected for development. The actual choices of reactor types for development were made for reasons other than safety—for reasons valid in a given time and context, but that no longer matter to us.

CHAPTER THREE

Competitive Private Enterprise

By 1954 the Shippingport and other early reactors had begun to provide form to what had been an inchoate vision of nuclear power a decade earlier. But the United States still had considerable leeway in how to develop a civilian nuclear power industry. This flexibility virtually disappeared, however, as a result of economic and political choices in the mid-1950s. The outcome was an industry organized along the lines of competitive private enterprise, relying exclusively on light water reactors.

Framing a Nongovernmental Nuclear Industry

The relationship between private enterprise and government has been ambiguous and difficult since the outset of the nuclear era. Much of the initial work of the Manhattan Project during World War II was contracted out to private business; du Pont, for example, managed a nuclear plant during the war. Other corporations, most notably General Electric and Union Carbide, were brought in at an early stage of the civilian research and development program in the mid-1940s; but whether they could or should make a profit on the activities was not clear at first.

This fundamental confusion and entanglement is evident in legislative provisions of the McMahon Atomic Energy Act of 1946,

which transferred federal nuclear power activities from the military to the Atomic Energy Commission. The act's preamble reads in part: "The development and utilization of atomic energy shall, so far as practicable, be directed toward . . . strengthening free competition in private enterprise."¹ In direct contradiction of its stated purpose, the act established a thoroughgoing government monopoly over the ownership and development of nuclear power. Yet at the same time the AEC had to rely heavily on private industry to help manage the AEC's installations, do some of the research and development, and perform most of the actual manufacturing and construction.

Many members of the Atomic Energy Commission and the congressional Joint Committee on Atomic Energy were sympathetic to private enterprise; they envisioned that industry would be brought fully into the civilian atomic energy business at some point, perhaps relatively early. David E. Lilienthal, first chairman of the AEC, was among the early proponents of a private nuclear enterprise. In a speech given in 1947 entitled "Atomic Energy and American Industry," he began to hint that industry should advance proposals to participate.² After leaving the AEC in 1950 Lilienthal became even more outspoken. In a popular article, "Free the Atom," he compared the U.S. government's monopoly on industrial nuclear power with Soviet practices, and called for fundamental revisions in legislation.³

Business responded first with informal inquiries, speeches, and articles on the prospects for industrial participation.⁴ Then firms and industrial groups seeking to participate in reactor research and development began to submit proposals. Between 1951 and 1954 the AEC authorized nineteen groups to explore the feasibility of nuclear power initiatives in the private sector; approximately forty utilities, equipment manufacturers, and construction companies were involved. By 1953, partly as a result of this interest expressed by in-

1. Atomic Energy Act of 1946, Public Law No. 79-585, chap. 724, 60 *United States Statutes at Large* 755.

2. Reprinted in U.S. Congress, Joint Committee on Atomic Energy, *Atomic Power and Private Enterprise*, 82d Cong., 2d sess., December 1952, pp. 191-193.

3. David E. Lilienthal, "Free the Atom," *Colliers*, June 17, 1950, pp. 13-14.

4. See for example "The Atom and the Businessman," *Fortune*, January 1949; "Prospects in Industrial Application of Atomic Energy" (speech by Philip Sporn, president, American Gas and Electric Service Corporation, October 7, 1949); and "Let Us Be Ourselves" (speech by Charles A. Thomas, Monsanto Chemical Company, June 11, 1950), all reprinted with others in *Atomic Power and Private Enterprise*, app. D, "A Chronology of Significant Developments, Statements, and Articles," pp. 159-401.

dustry, sentiment in Congress and at the policy-making levels of the AEC had shifted decisively in favor of a larger role for private industry.⁵

In 1954, at the request of President Eisenhower, the chairman of the Atomic Energy Commission, and the Joint Committee on Atomic Energy, Congress amended the Atomic Energy Act. The new law provided for nongovernmental ownership of nuclear power plants, protected corporate trade secrets with more liberal patent provisions, and otherwise encouraged a civilian industry.

Debate over whether ownership of electricity generation should be public or private was long past by the time nuclear power became a major political issue in the 1970s. But in the early 1950s it was the subject of heated debate. Opponents looked at the act of 1954 as a giveaway by the federal government to private industry. One public power advocate stated in congressional testimony: "It requires no great insight to see that the present contractors who have been running AEC plants, or who have had contracts for experimentation and development, have a running start on the whole field. They have the experienced personnel and the technical knowledge which will enable them to obtain control and determine the future industrial development of atomic energy."⁶ Congressmen Chet Holifield and Melvin Price, two key members of the Joint Committee on Atomic Energy, feared that the act could lead to a "transfer of atomic power development to private monopoly."⁷ Failing to block the changes of 1954 entirely, Holifield and others proposed numerous amendments to make the bill more favorable to public power and less favorable to private interests.

One amendment would have authorized the AEC to establish facilities for producing and distributing nuclear-generated electrical power (in partial competition with private industry). Another attempted to establish an Electric Power Liaison Committee to participate in decisions about commercial development of the technology; members would have been drawn from the Federal Power Commis-

5. For further details on the changing expectations of the role of private industry in nuclear power from 1947 to 1953 see George T. Mazuzan and J. Samuel Walker, *Controlling the Atom: The Beginnings of Nuclear Regulation, 1946-62* (Berkeley: University of California Press, 1984), esp. pp. 17-24.

6. Testimony of Benjamin Sigal, Congress of Industrial Organizations, in U.S. Congress, House of Representatives, *Legislative History of the Atomic Energy Act of 1954*, Report, 83d Cong., 2d sess., 1954, p. 2132.

7. *Ibid.*, p. 872.

sion and public power agencies like the Tennessee Valley Authority. On some of these issues, the votes were very close in at least one house of Congress. On authorizing the AEC to generate and sell electricity, the Senate at one point actually went along with the public power position.

In the end, the advocates of a private nuclear enterprise won a clear victory. The act expressly forbade the Atomic Energy Commission from becoming a commercial power producer.⁸ It did establish a special division of the Atomic Energy Commission to encourage rapid development of the industry and regulate health, safety, and security, but the legislation expressed no expectations that the AEC should guide the overall pattern of commercial development. There were only two concessions to the public power advocates. Private businesses were required to license their patents to others for the next five years, the objective being to avoid a monopoly by the large firms that had been working with nuclear power under AEC contracts. And public power companies were to be given preference in sales of excess electrical power from the AEC's research and weapons reactors. Neither clause turned out to have significant direct effects.⁹

Overall, the act of 1954 affirmed the position of the joint committee's majority:

The goal of atomic power at competitive prices will be reached more quickly if private enterprise, using private funds, is now encouraged to play a far larger role in the development of atomic power than is permitted under existing legislation. In particular, we do not believe that any developmental program carried out solely under governmental auspices, no matter how efficient it may be, can substitute for the cost-cutting and other incentives of free and competitive enterprise.¹⁰

Public power advocates tried again in 1956, with a bill introduced by two Democratic members of the joint committee, Sen. Al-

8. The private power issue was also involved in the Dixon-Yates controversy of 1953-55; see Aaron Wildavsky, *Dixon-Yates: A Study in Power Politics* (New Haven and London: Yale University Press, 1962).

9. Indirectly, sales of power from the Hanford reactor may have helped induce the Washington Public Power Supply System to invest heavily in nuclear power, with financially disastrous consequences; see Wayne H. Sugai, *Nuclear Power and Ratepayer Protest: The Washington Public Power Supply Crisis* (Boulder: Westview, 1987).

10. U.S. Congress, House of Representatives, *Legislative History*, 1954, p. 999.

bert Gore and Congressman Holifield. The legislation sought to have the AEC construct and operate six large-scale nuclear plants; these were to be additions to the projects already under way. Each new reactor was to be of a different design and in a different geographic region.

As we shall see, the AEC's reactor development program was already more diversified by this time than it had been in 1952, and in the eyes of many observers considerable progress was being made. But advocates of the Gore-Holifield Bill believed that development efforts were progressing too slowly, and that a government program could provide impetus for industry to move faster in its own commercialization efforts. One of the main sponsors of the legislation, Senator Gore, attempted to bolster his side's chances by pointing to the so-called international kilowatt race. He said that the Soviet Union, France, and Britain should not be allowed to outstrip the United States in a race where "anything other than victory is a disastrous defeat."¹¹ During this period the Soviets were examining seven different types of reactor, of which only a gas-cooled heavy water reactor had no counterpart in the American program. But the Soviets had announced a five-year program to build ten full-scale power plants with a total generating capacity of 2,500 megawatts. The British program was much narrower, concentrating on a gas-graphite reactor; their plan aimed for as much as 2,000 megawatts from sixteen reactors over ten years. The United States was somewhat behind the schedule announced by the Soviet Union, and somewhat ahead of Britain's.

Most leading officials of the AEC were opposed to the Gore-Holifield plan. Some had become converts to the private sector approach, but others merely believed that the appropriate objective was gradual development of advanced reactor types that would eventually operate at low cost, so that they would become competitive with fossil fuel sources. Rapid development of larger versions of relatively primitive reactor designs would not achieve this goal. One commissioner,

11. U.S. Congress, Joint Committee on Atomic Energy, *Hearings of Proposed Legislation for Accelerating the Civilian Reactor Program*, 84th Cong., 2d sess., 1956; Joint Committee on Atomic Energy, *Hearing on a Bill Providing for a Civilian Atomic Power Acceleration Program*, 84th Cong., 2d sess., 1956.

See also the analysis in Harold P. Green and Alan Rosenthal, *Government of the Atom* (New York: Atherton, 1963).

Thomas Murray, did favor Gore-Holifield. He expressed doubt that the United States would produce any substantial quantity of nuclear power by 1960 and blamed this on "the fact that the Government has prematurely abdicated to private industry the primary responsibility for building large power reactors."¹² Likewise supporting the legislation were most of the public power groups, such as the Rural Electric Cooperative Association and the Tennessee Valley Authority; so also did the AFL-CIO.

Arrayed on the other side were most of the privately owned utility companies, represented by the Edison Electric Institute. Westinghouse and General Electric expressed concern about certain provisions of the bill and its implications, particularly the drain that so many new reactor projects would put on skilled manpower. Neither expressed outright opposition, but both corporations had already selected light water reactors, and their testimony emphasized doubts about the readiness of other reactor types for commercial development.

The Gore-Holifield Bill passed the Senate but was defeated in the House; President Eisenhower reportedly would have vetoed it in any case.¹³ The proposal's defeat essentially ended the great debate over public versus private power. Whether the particular technical advances envisioned in Gore-Holifield would have proven significant is impossible to judge. But there is a reasonable prospect that the plan would have checked the momentum of private power advocates, and that the structure of the nuclear industry would have turned out differently—and perhaps better (see chapter 6 for further discussion).

One additional point bears mention. Throughout the debate over the Gore-Holifield Bill, virtually no attention was devoted to safety issues. The focus was on how best to bring practical nuclear power to fruition quickly.

Inducing Industrial Participation

With the passage of the Atomic Energy Act of 1954, the AEC faced a new challenge: if nuclear power was to be a private enterprise, then private industry would now have to be induced to take on the long

12. Quoted in Mazuzan and Walker, *Controlling the Atom*, p. 118.

13. As reported by Lewis Strauss and quoted in Mazuzan and Walker, *Controlling the Atom*, p. 120.

and risky process of investing huge sums to learn about and commercialize the technology. It was one thing in the early 1950s for industry to express interest, but quite another to undertake the difficult process of moving from reactor concepts, to small experimental reactors and prototypes, to commercial-scale plants capable of competing with electricity generated by fossil fuels.

To stimulate industrial participation, the AEC developed a Power Reactor Demonstration Program. Private concerns were invited to submit proposals for development, construction, and operation of various types of reactors. The commission then selected those proposals that seemed to offer reasonable prospects for advancing development of a particular type. To help make the costs and risks manageable, the AEC would subsidize the cost of fuel, conduct pertinent research and development work for free at the national labs, and help pay for some of the research and development conducted by private industry. The AEC did not provide subsidies for actual construction of power plants, because the act of 1954 forbade it.¹⁴

The Power Reactor Demonstration Project went through several rounds between 1955 and 1958, during which private industry submitted more than a dozen proposals. The AEC accepted most of these in some form. Proposals during the first round included those for two light water reactors, a small sodium-graphite reactor, and a fast breeder. The AEC's Technical Advisory Group noted that the proposed reactors were "quite experimental in nature," and they warned "not to depend upon any of these reactor power plants as an essential part of the supply to an electrical network."¹⁵ Nevertheless, the AEC agreed to work with all four groups on construction of demonstration reactors. For even if a particular reactor project did not work out well, four projects would provide a larger market for firms considering entry into the nuclear supply and service business. The AEC wanted such businesses to gear up for a future market, thus accelerating development of a competitive nuclear power industry.¹⁶

Another round, initiated in late 1955, was intended to bring

14. Joint Committee on Atomic Energy, *Accelerating the Civilian Reactor Program*, p. 109.

15. On the issue of subsidies see Harold P. Green, "The Strange Case of Nuclear Power," *Federal Bar Journal* 17 (1957): 100-128.

16. U.S. Atomic Energy Commission, "Power Demonstration Reactor Program," AEC 777/11, June 30, 1955, p. 30.

small, publicly owned utilities into nuclear power generation. The technical goal was small reactors (5 to 40 megawatts) potentially suitable for rural areas and small municipalities with relatively low demand for electricity. The AEC hoped such reactors might also prove attractive for export. To help small utility companies participate, the commission agreed to pay for the reactor portion of each plant, in addition to the financial inducements offered in the first round.

Seven electricity cooperatives and other small, public organizations submitted proposals. But most floundered on three problems: (1) the utility companies were too small to take much financial risk, yet the AEC insisted on firm ceilings on its expenditures; (2) the proposed reactors required too great a technological leap for a demonstration program; (3) the utilities lacked the requisite engineering talent. Eventually, the AEC dropped the entire objective of developing commercial reactors for small utilities.¹⁷ Had it proceeded, the result might have been much smaller commercial power plants than are common today, and partial ownership of the plants by the federal government. Size and ownership proved important in the demise of the nuclear enterprise (see chapters 5–7).

Until the early 1960s, the AEC continued to introduce various programs for speeding up the private sector's participation in nuclear power.

The Price-Anderson Indemnity Act

It quickly became apparent to privately owned corporations that special arrangements would be necessary for liability insurance. According to a report issued in the mid-1950s by the Atomic Industrial Forum (a leading association of firms interested in nuclear power), the problem of liability for catastrophic accidents was a "serious immediate threat to the vital national interest" of establishing a nuclear power industry.¹⁸ The AEC formed an Insurance Study Group in early 1955, and by the following year private insurance companies had worked out a system for providing each nuclear installation with \$60 million of coverage for property damage and liability from accidents

17. Ibid., p. 36. For a survey of the first and second rounds see also Wendy Allen, "Nuclear Reactors for Generating Electricity: U.S. Development from 1946 to 1963," RAND Corporation report R-2116-NSF (Santa Monica, 1977), pp. 39–66.

18. Mazuzan and Walker, *Controlling the Atom*, p. 105.

affecting the public. But this level of coverage was considered inadequate, given the potential for catastrophic accidents.¹⁹

As early as 1954, during the hearings on revising the Atomic Energy Act, a spokesman for the industry suggested that government provide liability protection above what would be available through regular insurance companies. And at subsequent hearings of the joint congressional committee throughout the mid-1950s, industry witnesses were virtually unanimous in asserting that government liability coverage above the amount available privately was essential for the commercial nuclear power industry to proceed. A spokesman for one nuclear reactor vendor testified, "At present I see no alternative but to recommend that work on the Dresden Station be halted as soon as practicable after the end of this session of Congress in case appropriate legislation has not been passed by that time. Also, as I now see it, it is my view that General Electric should not take on any other comparable project if it appears that appropriate legislation will not be passed."²⁰ General Electric could not proceed "with a cloud of bankruptcy hanging over its head."²¹ The AEC and joint committee had initially been skeptical of the need for early federal action, but industry's argument that failure to act soon would interfere with the development of nuclear power by the private sector quickly shifted a majority toward supporting government liability coverage.²²

The next question was how much. The AEC argued that government should assume unlimited liability above the \$60 million of conventional insurance, but Sen. Clinton Anderson, chairman of the joint committee, argued for a limit of \$500 million. His motivation was partly that a cap on the government's liability would make passage of the legislation easier in the Senate. The AEC made a series of calculations that suggested damages could run closer to \$900 million, but the joint committee opted for the lower figure.²³ Partisan skir-

19. Ibid., pp. 93–100, discusses deliberations before 1956 pertaining to liability insurance.

20. *Congressional Record*, 85th Cong., 1st sess., 1957, p. 10719.

21. Ibid.

22. This is an excellent illustration of the general tendency of governments in market-oriented societies to solicit the advice of business, and then to go a long way toward offering the accommodations requested. See Charles E. Lindblom, *Politics and Markets: The World's Political-Economic Systems* (New York: Basic Books, 1977).

23. Mazuzan and Walker, *Controlling the Atom*, pp. 102–121, discusses the deliberations of 1956.

mishing between House Democrats and Republicans kept the legislation from coming to a vote in 1956, but the Price-Anderson Indemnity Act as reintroduced in 1957 was favored by almost every member of the joint committee, had widespread support in Congress, and was backed by the president; both private and public utilities also approved of it, as did reactor manufacturers and auxiliary nuclear industries.

While the hearings were going on in 1957, Brookhaven National Lab released its study of the costs of the worst possible reactor accident, which they estimated to be as much as \$7 billion in 1957 dollars.²⁴ The joint committee did not alter the liability limit set the previous year, however, and there was very little attention to the bill from any other members of Congress. There was "no significant opposition" to it in the Senate, and it provoked so little controversy in the House that the chamber "had a difficult time maintaining a quorum to conduct business on the bill." Mazuzan and Walker suggest that this "show of massive indifference reflected the deference House members afforded the Joint Committee"; it also demonstrates poignantly how uncontroversial the issue of reactor safety was at the time.²⁵

Several unions did object to the legislation on grounds that government indemnification could reduce the incentives for stringent safety criteria. And Congressman Holifield made an impassioned plea for stopping or at least amending the legislation on the grounds of safety. He argued that it would be safer during the early years to construct reactors at isolated sites "under Government supervision and where direct Government responsibility is exercised." He emphasized the lack of knowledge then accumulated about the probability of reactor accidents, reminded colleagues about a prominent, recent case where the AEC had cavalierly handled a safety report by its own Safeguards Committee, and argued against prematurely taking "blind risks with human lives."²⁶ But Holifield's appeals evoked little response from fellow legislators.²⁷

24. U.S. Atomic Energy Commission, "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants," WASH-740 (Washington, 1957).

25. Mazuzan and Walker, *Controlling the Atom*, pp. 207–213, discusses the action of 1957 on Price-Anderson; the quotations are from p. 211.

26. Mazuzan and Walker, *Controlling the Atom*, pp. 118–119, 211–213; the quotations are from p. 118.

27. Holifield also opposed the bill on the grounds that it would provide another

The legislation passed both houses of Congress easily, thus making final the turning over of commercial nuclear power to private enterprise.

The Increasing Role of Cost Considerations

While Congress was working out the institutional arrangements for a private nuclear power industry and the AEC was inducing industrial participation, research and development continued on various reactor technologies. Whereas cost considerations were peripheral in reactor selections of the 1940s and early 1950s, they played an increasing role as commercial application by private industry began to build momentum in the late 1950s.

The Plan of 1954

Shortly before the Atomic Energy Act of 1954 was passed, the Joint Committee on Atomic Energy asked the AEC to devise an expanded reactor program for the next three to five years. The commission responded by resurrecting its earlier development plan. The favored reactor types were the same ones that had been proposed by the AEC in 1952 and then canceled by the Eisenhower administration owing to budget constraints. These were the fast breeder reactor, the homogeneous reactor, the sodium-cooled, graphite-moderated reactor, and the pressurized water reactor being constructed at Shippingport, Pennsylvania. The new program also included research into other promising but as yet undeveloped reactor types.²⁸

Over the next few years seven other types of reactor came to be included in the development program. The process by which the AEC

government subsidy to nuclear power and weaken congressional control over spending by authorizing in advance the expenditure of up to \$500 million for each catastrophic accident. But Holifield was actually attempting to make another plea for public control of nuclear power, asserting in part: "In my view, this legislation is unnecessary and unwise. If the risks are negligible, as the proponents of this bill contend, there is no reason why the Government should assume [the] potential liabilities. . . . If the risks are real and substantial, then reactor development programs should continue to be developed under direct Government supervision and control at isolated locations, with the continued promise of safety exhibited in the record of government performance." U.S. Congress, Joint Committee on Atomic Energy, *Selected Materials on Atomic Energy Indemnity Legislation*, 89th Cong., 1st sess., June 1965, p. 130.

28. U.S. Congress, Joint Committee on Atomic Energy, Subcommittee on Research and Development, *Report of the Subcommittee on Research and Development on the Five-Year Reactor Development Program Proposed by the AEC*, Washington, 83d Cong., 2d sess., March 1954.

made decisions about these reactors reveals the extent to which economic considerations took priority in the pursuit of private nuclear power.

The first reactor type added to the newly established program was the boiling water reactor, a variation of the pressurized water reactor used in submarines. During the 1940s scientists believed it was unsafe to allow water to boil in reactors. This is why they originally turned to pressurized water reactors, for pressurization prevents boiling. But experiments conducted over a period of five years at Argonne National Lab showed that boiling water did not lead to the expected instability.²⁹

This discovery opened up the possibility that light water reactors could be simplified, and could be operated at low pressure, without steam generators, and with less pumping power. Designers believed that these simplifications would reduce capital costs. The Reactor Division added an experimental version of the boiling water reactor to the AEC program,³⁰ and General Electric soon adopted this reactor concept as the primary focus in its approach to commercial nuclear power.

The history of the boiling water reactor illustrates two important points. First, throughout the mid- and late 1950s, it was the relative economic potential of reactors that was the dominant criterion in the selection process. The boiling water reactor was attractive because it could apparently be built for significantly lower cost than a pressurized water reactor.

Second, although not the primary issue, some aspects of safety were examined at the earliest stages of a reactor's development. Before a reactor type was seriously considered for development, it had to be shown that the safety problems inherent in it could at least in principle be overcome. The boiling water reactor was ruled out until it

29. In fact the experiments showed that boiling water reactors could be designed so that an increase in reactor power caused an immediate decrease in the rate of chain reaction. See Samuel Untermyer, "Direct Steam Generation for Power," *Nucleonics* 12, no. 7 (1957): 44; Andrew W. Kramer, *Boiling Water Reactors* (Reading, Mass.: Addison-Wesley, 1958), p. 3.

30. See Oliver Townsend, "The Atomic Program in the U.S.," in Phillip C. Jessup, ed., *Atoms for Power: United States Policy in Atomic Energy Development* (New York: American Assembly, 1957), pp. 35-79; U.S. Congress, Joint Committee on Atomic Energy, Subcommittee on Research and Development, *Current Statement of the Atomic Energy Commission on the Five Year Reactor Development Program*, 84th Cong., 1st sess., 1955.

passed this test. This is by no means the same as looking for an especially safe reactor, but at least nuclear decision makers were guarding against especially unsafe ones.

Six other reactors were selected for development in the mid-1950s (table 3.1) Each offered one or more attractions in terms of economic potential. For example, reactors with liquid metal coolant were expected to operate at higher temperatures than those cooled by water, leading to more power for a given amount of fuel and capital expense. Similarly, lower pressures were expected to reduce construction costs;³¹ gas or hydrocarbon coolants (similar to automobile antifreeze) would offer lower corrosion levels, allowing the use of ordinary steel rather than more expensive alloyed steel;³² heavy water moderation would improve fuel efficiency;³³ and because gas becomes

TABLE 3.1 Economic Advantages of Six Advanced Reactors

Type	Advantages
Liquid metal-fueled homogeneous reactor	Higher temperature Lower pressure
Organic reactor	Higher temperature Lower pressure Less corrosion
Gas-cooled, heavy water-moderated reactor ^a	Improved fuel efficiency Higher temperature Less corrosion Less radioactivity absorbed by coolant
Sodium-cooled, heavy water-moderated reactor	Higher temperature, lower pressure Improved fuel efficiency
Heavy water-moderated, heavy water-cooled reactor	Natural uranium fuel
Gas-cooled, graphite-moderated reactor	Natural uranium fuel

^aMost proposals by private industry were for versions of reactor types already under development by the AEC; this was the first new type proposed by an industrial group.

31. Subcommittee on Research and Development, *Current Statement*.

32. *Ibid.*

33. See U.S. Congress, Joint Committee on Atomic Energy, *Hearings on the Development, Growth and State of the Atomic Energy Industry*, 85th Cong., 2d sess., 1958, pp. 397-409.

less radioactive than water or liquid metal, its use as a coolant was expected to simplify reactor maintenance and reduce costs.³⁴

One particularly noteworthy candidate was the sodium-cooled, heavy water-moderated reactor. It combined the most efficient coolant, sodium, with the best of the possible moderators, heavy water. It offered the prospect of low capital costs as well as low fuel costs, so that the reactor had excellent long-term economic potential. But sodium and water are chemically incompatible; they explode on contact, so that complete separation of the two materials would have to be guaranteed for this reactor type to be practical. The AEC decided to wait for a study of the feasibility of keeping the sodium and water separated before actually committing itself to building a version of this reactor.³⁵

The manner in which this potential hazard was treated illustrates again the one safety criterion used in the reactor selection process: economics ruled supreme, but development of a potentially economic reactor would not be undertaken unless major safety problems associated with it could be overcome at least in principle. The decision process screened out especially unsafe types of reactor, but on the other hand did not seek out especially safe ones. If it had, the sodium-cooled, heavy-water-moderated reactor would not even have been considered.

During this period two additional reactors were championed by the congressional joint committee: heavy water reactors, and gas-cooled, graphite-moderated reactors. Compared with the other reactors under consideration, these were based on relatively mature technologies. As we noted in discussing the Gore-Holifield Bill, the committee favored such reactors as part of a long-standing campaign for quick construction of full-scale reactors.³⁶

The joint committee also favored nuclear reactors for geopolitical reasons. The nuclear nations were still perceived to be in a kilowatt race, and for the United States to keep up it would have to build large

34. For further detail see Robert L. Loftness, *Nuclear Power Plants: Design, Operating Experience and Economics* (New York: D. Van Nostrand, 1964), pp. 235-274.

35. U.S. Congress, Joint Committee on Atomic Energy, *Authorizing Legislation for FY 1958*, p. 177.

36. The heavy water and gas-graphite reactors were the obvious candidates for large-scale construction. Development of both began during the war, and by 1950 large versions of both were being built: the heavy water reactor by the AEC as a plutonium producer, the gas-graphite reactor by the British as a power producer.

reactors of its own. To the joint committee, it was vital that the United States do so. As one senator put it, "If we are outdistanced by Russia in this race, it would be catastrophic. If we are outdistanced either by the United Kingdom or France, there would be a tremendous economic tragedy to our commerce and the international commerce of this great nation of ours."³⁷

The joint committee urged development of the heavy water and gas-graphite reactors for a third reason: both were attractive for export because they operated with natural uranium as fuel. Most countries lacked their own enrichment plants and were therefore interested in natural uranium reactors, such as Britain's gas-graphite type and Canada's heavy water reactor (CANDU). The joint committee believed that in the future American nuclear industry would have to be able to supply natural uranium reactors to compete successfully in foreign markets.³⁸

The AEC was unenthusiastic, in part because the technologies were relatively unsophisticated and therefore had questionable long-term economic prospects.³⁹ When formal studies cast doubt on the gas reactor's financial prospects, it was redesigned to use enriched fuel and otherwise to reduce costs. The high temperature gas reactor thus acquired long-term potential (see chapter 6), but lost its original rationale for an export market.⁴⁰ Moreover, the AEC decided to build only small, experimental versions of the two reactors, not reactors of the nearly commercial size desired by the joint committee.⁴¹

37. Statement by Sen. John O. Pastore, in Joint Committee on Atomic Energy, *Accelerating the Civilian Reactor Program*; quoted in Frank G. Dawson, *Nuclear Power: Development and Management of a Technology* (Seattle: University of Washington Press, 1976), p. 105.

38. The committee's push for the heavy water and gas-graphite reactors is evident throughout the hearings of 1956.

39. The reactor would have had to be very large to accommodate the graphite moderator, which would lead to higher capital costs. It would also have had to operate at relatively low temperatures and be cooled by gas, a material with mediocre heat transfer properties. This meant that the reactor would generate relatively small amounts of power per unit of fuel and capital, which would contribute to increased fuel and capital costs. See Dawson, *Nuclear Power*, pp. 108–109.

40. U.S. Congress, Joint Committee on Atomic Energy, *Technical Aspects of the Report on the Gas-cooled Graphite-moderated Reactor*, 85th Cong., 2d sess., 1958.

41. On the gas reactor see Joint Committee on Atomic Energy, *Authorizing Legislation for FY 1959*, p. 26. Development was to begin with an experimental reactor larger and more complex than the AEC's other experimental reactors, but an experimental reactor all the same. It was designed to provide data on "a variety of fuel

The larger point is that again reactors were selected for reasons other than safety.⁴² Geopolitical factors and suitability for export weighed heavily in congressional deliberations; these were resisted by the AEC, but only insofar as they failed to satisfy the AEC's driving concern for low cost potential. Safety and suitability for widespread use in society were not explicitly considered.

Results of the Reactor Competition

By 1958 the AEC was developing eleven different types of reactor in conjunction with private industry (Table 3.2). The two light water reactors (the pressurized water reactor and boiling water reactor) were advancing much more rapidly than the others: prototypes of the two were already being built in 1958, whereas prototypes were only being planned for most of the others. Further, the prototypes of light water reactors were larger and more numerous, and three were actually being built without any support from the AEC, indicating near-term commercial prospects.

In 1959 the Reactor Development Division began to compare the various reactors and weed out those considered less promising. The first to be downgraded was the heavy water reactor, on the grounds that it did not hold "the same economic promise as the other types of reactors for application in the U.S."⁴³ Recall that the heavy water

elements, materials, and components and to test operation with different coolant gases," rather than generate power as the joint committee wanted. See U.S. Congress, Joint Committee on Atomic Energy, *Hearings on AEC Authorizing Legislation for FY 1960*, 86th Cong., 1st sess., 1959, p. 135.

On the heavy water reactor see for example U.S. Congress, Joint Committee on Atomic Energy, *Authorizing Legislation for FY 1958*, 85th Cong., 1st sess., 1957, p. 552. See also U.S. Congress, Joint Committee on Atomic Energy, *Hearings on AEC Authorizing Legislation for Fiscal Year 1959*, 85th Cong., 2d sess., 1958, p. 28.

42. There is however one sense in which relative safety did enter into the deliberations. As discussed in detail in chapter 4, once a reactor was selected for development safe operation became an important goal. Thus if a selected reactor type was less safe than others, greater design and development precautions would have to be taken on it. These precautions would increase its costs, and because cost estimates were the measure of relative attractiveness, the safety-related cost increases would have made the reactor less attractive.

43. The studies proceeded as follows: several alternative designs for each type were evaluated; for each type, the design that would lead to the most economical power plant that could be built beginning in January 1960 was selected; detailed cost estimates were made for the selected designs; and the cost estimates were compared. See U.S. Congress, Joint Committee on Atomic Energy, *Authorizing Legislation for FY 1960*, pp. 512-515; the quotation is from p. 513.

Table 3.2 Civilian Reactor Development Program, 1954–66

Experimental Reactors			Prototype Reactors				Commercial Reactors	
Reactor Type	Name	Status	Name	Capacity (in megawatts)	Status	AEC's share of cost (in percent)	Name (year announced)	Capacity (in megawatts)
Pressurized water	None		Submarine Converted Carrier	160	Operated	100	Connecticut Yankee (1962)	575
			Indian Point	151	Operated	100	San Onofre (1963)	436
			Yankee	175	Operated	0	Indian Point 2 (1965)	873
						18	Turkey Point 3 (1965)	666
							Ginna (1965)	490
							Point Beach 1 (1966)	497
							Robinson 2 (1966)	665
							Salem 1 (1966)	1,090
							Surry 1 (1966)	775
							Surry 2 (1966)	775
Boiling water	Borax 1,2,3,4,5 EBWR Valecitos (built by industry)	Operated Operated Operated	Dresden	200	Operated	0	Oyster Creek (1963)	620
			Elk River	22	Operated	90	Nine Mile Point (1963)	670
			Pathfinder	62	Under construction	22	Pilgrim (1965)	610
			Humboldt Bay	50	Operated	0	Millstone 1 (1965)	652
			Bonus	16	Operated	74	Dresden 2 (1965)	800
			Big Rock	70	Under construction	14	Dresden 3 (1966)	800
							Monticello (1966)	536
			La Crosse	50	Under construction	69	Quad Cities 1 (1966)	800
							Browns Ferry (1966) and others	1,067
Organic moderated and cooled	OMRE	Operated	Piqua	10	Operated	79		None
	EOCR	Canceled	Large prototype	50–100	Canceled			
Aqueous Homogeneous	HRE 1	Operated	Wolverine	10	Canceled			None
	HRE 2	Operated	Pennsylvania Power & Light	150	Canceled			
Liquid metal-fueled	LMFRE	Canceled		None				None
Natural uranium, heavy water	HWCTR	Operated	Carolinas-Virginia Large prototype	17	Operated	31		None
				100	Canceled			
Gas-cooled, graphite-moderated	EGCR	Constructed but never operated	Peach Bottom	40	Under construction	30	Fort St. Vrain (1965)	330
Gas-cooled, heavy water-moderated	Research and development	Canceled	East Central-Florida West Coast Nuclear Group	58	Canceled			None
Sodium-cooled, heavy water-moderated	Research and development	Canceled	Chugach	10	Canceled			None
Sodium-cooled, graphite-moderated	SRE 1	Operated	Hallam	75	Operated	74		None
	SRE 2	Canceled						
Liquid metal fast breeder	EBR 1 EBR 2	Operated Operated	Fermi Several large prototypes	90	Operated Planned	74		None

Sources: U.S. Congress, Joint Committee on Atomic Energy, *Authorizing Legislation, 1955–60; Development, Growth, and State of the Atomic Energy Industry, 1955–60*; Wendy Allen, “Nuclear Reactors for Generating Electricity: U.S. Development from 1946 to 1963,” RAND Corporation report R-2116-NSF (Santa Monica, 1977).

reactor was originally intended for export to nations without a source of enriched uranium. Nevertheless, owing to the unfavorable cost estimates, the AEC canceled its plan to build a prototype.⁴⁴

Also in 1959 the AEC undertook a major study of its homogeneous reactor projects.⁴⁵ It was obvious even before the study that the homogeneous reactors could not compete with others in the short run; many technical problems still remained and no prototype versions had yet been built. But the study concluded that neither were homogeneous reactors worth developing for the long run. The director of reactor development described the situation as follows:

It would require at least ten years to bring fluid fuel [that is, homogeneous] reactors to the present state of development of the other concepts. . . . During this development period further advances in technology and cost reductions will also be achieved on these more developed reactor concepts, so that even then the fluid fuel reactors will remain at a competitive disadvantage. In view of this, undertaking the extensive and costly program required for the development of any one of the fluid fuel reactor concepts is considered unjustified.⁴⁶

Next to be canceled was the sodium-cooled heavy water reactor, in mid-1959. A task force established to assess its prospects concluded that although the reactor continued to seem promising, the separation of water and sodium still could not be guaranteed. Considerably more experimental and development work would have to be performed before an operating version could be built.⁴⁷ With this finding, the industrial group that had been working on the reactor withdrew and development of the type ended. In effect, the sodium-cooled heavy water reactor had failed to satisfy the constraint of being safe at least in principle.

44. Basic research continued, along with construction of two small reactors already in progress.

45. These were the aqueous homogeneous reactor, the liquid metal-fueled reactor, and the molten salt reactor (for the air force), which we have not discussed.

46. U.S. Atomic Energy Commission, Memo 152/128, May 28, 1959 (unpublished memorandum, U.S. Department of Energy, Historian's Office), p. 3. Basic research continued, but plans were canceled for two prototypes and one homogeneous reactor experiment. The impetus for continuing at all was the potential of the aqueous homogeneous reactor to become a breeder.

47. U.S. Congress, Joint Committee on Atomic Energy, *Hearings on the Development, Growth, and State of the Atomic Energy Industry*, 86th Cong., 1st sess., 1959, p. 86.

The sodium-cooled, graphite-moderated reactor was downgraded in 1960. Because of its sodium cooling the reactor still seemed to have long-term potential to achieve low costs, but the fast breeder reactor also used sodium cooling and seemed even more promising.⁴⁸ The gas-cooled heavy water reactor was canceled when the industrial group working on it concluded that their planned prototype would be too expensive, and therefore withdrew from the project. The AEC concurred that the reactor type did not appear economically promising.⁴⁹ Finally, plans for a prototype of the organic moderated and cooled reactor were canceled in 1962. The Reactor Division believed that "the technical problems could have been solved, [but] there appeared to be no marked advantages either technical or economic, over the light water systems."⁵⁰

After the reactor types considered less economically viable were canceled, the AEC's reactor development program was reduced by 1962 to four reactors. The high temperature gas reactor and the fast breeder were directed at the long term.⁵¹ Only the boiling water reactor and the pressurized water reactor, each cooled and moderated by light water, were left as near-term choices.

The primary reason that light water reactors had outdistanced all others by the 1960s was the substantial head start they had received from the navy submarine program and the subsequent Shippingport reactor.⁵² While the more advanced reactors were still undergoing research and experimentation, successively larger versions of the technologically less sophisticated light water reactors were gradually improving their design, engineering, and material composition. Thus as the AEC's Reactor Division searched for low-

48. It was too late to cancel construction of a prototype version of the reactor, but plans for an advanced experimental version and for additional prototypes were dropped. See for example U.S. Congress, Joint Committee on Atomic Energy, *Hearings on AEC Authorizing Legislation for Fiscal Year 1961*, 86th Cong., 2d sess., 1960, pp. 302, 482ff.

49. U.S. Congress, Joint Committee on Atomic Energy, *Hearings on the Development, Growth, and State of the Atomic Energy Industry*, 87th Cong., 2d sess., 1962, p. 73.

50. U.S. Congress, Joint Committee on Atomic Energy, *Hearings on the Development, Growth, and State of the Atomic Energy Industry*, 88th Cong., 1st sess., 1963, p. 44.

51. Both were believed to have the potential to breed as well as achieve substantial gains in fuel efficiency. They were included in a new, advanced reactor development program.

52. This favored position had, in turn, been made possible by the relative familiarity of water-based engineering and by other factors discussed in previous chapters.

cost reactors by developing relatively exotic reactor types, the technologically mundane light water reactors developed into practical machines.

If some of the other reactors had been developed to their mature states, it is quite possible that they would have proven less expensive, more reliable, or safer than the light water reactors. Indeed, most of the advanced reactor concepts were still considered to have good technical potential at the time they were canceled. But the only way to realize their potential was to continue development. Because these reactors still were in relatively early stages, this would have required years of additional work and hundreds of millions of more dollars. Such expenditures were hard to justify in light of the apparent success of light water reactors.⁵³

Decision making in the 1950s came to emphasize development of a private nuclear industry. Public power advocates lost in congressional battles, and legislators provided the legal structure necessary for an American nuclear industry based on private enterprise. This pursuit of private power figured centrally in the selection, development, and later cancellation of the various reactor types. Reactors were selected on the basis of their economically appealing features, and canceled because they could not compete economically with light water reactors. If the nuclear enterprise was to be private and private firms were opting for light water reactors, continued emphasis on alternative reactor types would have been inconsistent with the overarching goal.

From the perspective of the early 1960s, these technical, political, and economic events did not seem especially remarkable. After all, some design approach must be chosen over others in any technological development. Choosing the most economical approach seemingly made good sense. And choosing private enterprise over public enterprise seemed compatible with the social, political, and economic mores and preferences of the time. Yet these commonplace patterns helped set the stage for the demise of the American nuclear power industry.

53. Numerous other reactor concepts were still being explored and advocated in the 1960s, especially the fast breeder, as discussed in U.S. Atomic Energy Commission, *Civilian Nuclear Power: A Report to the President*, 1962, app. 8, "Recommendations on Central Station Power Reactors by the General Advisory Committee" (Washington, 1962), pp. 81-85.

CHAPTER FOUR

Engineered Safety

Technical, economic, and political considerations dominated early choices about civilian nuclear power. Reactors did have to pass a preliminary test of safety-in-principle, but beyond that were evaluated largely on the basis of economic suitability for a private nuclear industry. Safety was more a constraint than an objective in this process, and public acceptability was not directly addressed.

After a reactor type had been selected for development, however, safety considerations became an important part of the development, commercialization, and licensing process. In this chapter we analyze the strategies used by nuclear decision makers as they attempted to make their potentially economical reactors relatively safe. We refer to these strategies and tactics as “add-on,” or “engineered,” safety, because they were not inherent in the reactor type itself.

Early Nuclear Safety Strategies

The first formal nuclear safety organization was the Atomic Energy Commission’s Reactor Safeguards Committee, established in 1947. Comprising leading atomic scientists from outside the AEC and led at the outset by Edward Teller, the committee’s function was to determine whether the AEC could build reactors without endangering public safety. The committee’s general approach was cautious, for nuclear

energy was still a very uncertain field. The AEC and the national labs had accumulated little experience with reactors and their operation and had virtually no basis for estimating the likelihood or effects of reactor accidents. As Teller noted some years later:

We could not follow the usual method of trial and error. This method was an integral part of American industrial progress before the nuclear age, but in the nuclear age it presented intolerable risks. An error in the manufacture of an automobile, for instance, might kill one to ten people. An error in planning safety devices for an airplane might cost the lives of 150 people. But an error allowing the release of a reactor's load of radioactive particles in a strategic location could endanger the population of an entire city. In developing reactor safety, the trials had to be on paper because actual errors could be catastrophic.¹

Because the possibility of serious accidents could not be ruled out, the Reactor Safeguards Committee decided to continue a practice begun by the Manhattan Project of keeping reactors isolated as much as possible from society. That way, if a serious release of radioactivity did occur the effects would be minimized. Each reactor was to be surrounded by two concentric areas: an unpopulated inner area under the complete control of the AEC, and an outer area with a population of no more than 10,000. The actual size of the two areas depended in part on the power of the reactor: the greater the power, the larger the areas. The size of the outer area depended also on the type of reactor and on the meteorology, hydrology, and seismology of the geographical region.²

The first major crimp in the AEC's plans to be caused by safety considerations arose over a reactor to be used for testing and experimentation. The AEC originally planned to build this materials testing reactor at the Argonne National Lab just outside Chicago, because scientists there would be conducting many of the experiments connected with it. But the Reactor Safeguards Committee ruled that the

1. Edward Teller with Allen Brown, *The Legacy of Hiroshima* (Garden City, N.Y.: Doubleday, 1962), p. 104.

2. Richard G. Hewlett and Francis Duncan, *Atomic Shield, 1947-1952* (University Park: Pennsylvania State University Press, 1969), p. 196. Meetings of the Safeguards Committee in June and September 1948 are summarized in an unpublished memorandum by Edward Teller, "Statement on Danger Area Regulations and on Schenectady Intermediate Reactor," AEC Archives, November 17, 1948, which is cited and discussed in Hewlett and Duncan, *Atomic Shield*, pp. 195, 204.

materials testing reactor was too large to be built so close to a city. Either the reactor would have to be redesigned and made less powerful, or it would have to be moved to a less populated site.

The director of Argonne, Walter Zinn, who might have been expected to fight for his lab's project, instead endorsed remote siting as a reasonable policy: "For a nation with the land space of ours and with the financial resources of ours, adopting a very conservative attitude on safety is not an unnecessary luxury."³ In fact, it was Zinn who had originated the idea of establishing a remote site where early versions of reactors could be tested. This proposal was "most enthusiastically" endorsed by the Reactor Safeguards Committee.⁴ In May 1949, only a year after the proposal first surfaced, the AEC approved a reactor testing site in a barren desert section of Idaho some forty miles from Idaho Falls, then a city of 20,000.⁵ In addition to the materials testing reactor, the first versions of the liquid metal fast breeder reactor and other reactors were constructed there.

One of the few early reactors not built at the test site was the first version of the intermediate reactor. Scientists at Knolls Atomic Power Laboratory, just outside Schenectady, New York, proposed to build it nearby, some ten miles from any heavily populated areas. Given the size of the reactor, this site caused some concern among members of the Reactor Safeguards Committee. Yet a more remote location might have prevented KAPL from continuing its research, and the committee feared this "would be disastrous to the leadership of the United States in atomic energy." In fall 1947 the committee therefore "concluded unenthusiastically that a location near Schenectady might be acceptable."⁶

In an effort to make the reactor more suitable for proximity to an urban area, scientists at KAPL developed a new tactic aimed at reducing or eliminating the amount of radiation that could be released in an accident. They proposed to enclose the entire reactor facility in a gas-tight steel sphere. It would be designed to withstand "a disruptive core explosion from nuclear energy release, followed by sodium-

3. Letter from Walter H. Zinn to James B. Fisk, July 23, 1948, AEC Archives: cited in Hewlett and Duncan, *Atomic Shield*, p. 196.

4. Edward Teller, letter to George L. Weil on behalf of the RSC, September 10, 1948, AEC Archives; cited in Hewlett and Duncan, *Atomic Shield*, p. 203.

5. C. P. Russel, *Reactor Safeguards* (New York: Macmillan, 1962), p. 19.

6. Hewlett and Duncan, *Atomic Shield*, p. 186.

water and air reactions,”⁷ and thus to contain within the facility “any radioactivity that might be produced in a reactor accident.”⁸ The AEC accepted this proposal, which then became a major component of safety efforts at all civilian nuclear plants. The KAPL reactor was still to be built in a relatively unpopulated area, so containment was not considered a complete replacement for remote siting.

The Reactor Safeguards Committee made a number of other safety-related decisions in its early years. In approving for Argonne a small research version of the materials testing reactor, for example, the committee required strict limits on the amount of plutonium and radioactive waste that could be generated. In evaluating this project as well as the one at KAPL, the committee considered not only the risk of accidents but also the potential for sabotage. In addition, the committee discussed in a preliminary way a variety of other safeguards, including various automatic safety devices such as those for emergency cooling of a reactor by flooding.⁹

Safety in the Submarine Program

By 1949 land-based prototypes of the pressurized water reactor and intermediate reactor were being built as part of the AEC’s submarine program. The reactors that would actually be placed in the submarines were to be constructed soon after,¹⁰ but the techniques of remote siting and containment used to protect against the effects of serious accidents in land-based reactors could not be applied to the seafaring versions: “Margins of safety for a nuclear powered submarine could not be guaranteed in the same way that they were with land-based reactors. Since the sixty-man submarine crew had no avenue of escape while the ship was at sea and major ports were generally large populations centers, ‘remote siting’ could not be relied upon to ac-

7. Russel, *Reactor Safeguards*, p. 20.

8. Richard G. Hewlett and Francis Duncan, *Nuclear Navy, 1946–1962* (Chicago: University of Chicago Press, 1974), p. 176.

9. Hewlett and Duncan, *Atomic Shield*, pp. 188, 203.

10. The land-based versions provided experience in building such reactors, for comparable reactors had not yet been built. They also provided an opportunity to uncover any serious flaws in reactor designs before construction of the seafaring versions.

ceptably limit the consequences of an accident. Nor could containment be reasonably engineered for a submarine.”¹¹

This led scientists and engineers working on nuclear-powered submarines to devise a very different way of addressing the potential for serious releases of radioactivity. Rather than use remote siting and containment to mitigate the effects of accidents, they worked on greatly reducing the likelihood of an accident occurring in the first place. Most of the tactics developed toward this end constituted unusually stringent applications of standard industrial practices, such as quality control, operator training, and program auditing. But two of the tactics were less common to industrial practices and seem to have been deliberately devised to reduce the probability of serious accidents on submarines.¹²

The first was to design the reactor with wide margins for error. Cars and most other machines are built to withstand typical operating conditions, but submarine reactors were built to withstand “the worst credible set of circumstances, rather than . . . average or probable conditions.”¹³ Each of the components had to be constructed of material that could withstand substantially higher temperatures and pressures than were likely during operation. And each was designed to be operated for considerably longer than was likely to be required.

Second, redundancies were built into the reactor in case a system or component failed in spite of being built to withstand extreme conditions.¹⁴ More than one means would be available to perform each safety function. Thus if one system for injecting the control rods into the core failed, another independent system could be used. Backup pumps would be available if a primary set of pumps failed to operate. If a valve became stuck, a different system for operating the valve or an alternate valve could be employed.

By the early 1950s, even though the major reactor selections were still being made with little explicit attention to safety, two distinct

11. E. S. Rolph, *Nuclear Power and the Public Safety* (Lexington, Mass.: Lexington Books, 1979), p. 24.

12. Because the nuclear submarine files are still partly classified, we do not have specific examples of the application of these two tactics.

13. Adm. H. G. Rickover, director, Naval Nuclear Propulsion Program, in *Nuclear Powerplant Safety Systems*, Hearings before the Subcommittee on Energy Research and Production, Committee on Science and Technology, U.S. House of Representatives, May 22–24, 1979, p. 1042.

14. Ibid.

strategies had begun to emerge for adding on safety. The one for submarines aimed at preventing accidents through redundancies and wide margins for error, the one for land reactors at keeping the public safe even if accidents should occur—through containment and remote siting. These two strategies were still in rudimentary form in the early 1950s, and they were employed separately rather than jointly. But even by this early date, an outline had begun to emerge of the approach to safety that the AEC would refine and extend in the next several decades.

The Basic Design Philosophy: “Defense in Depth”

By 1960 the AEC had integrated the safety strategies developed for submarines with those developed for land-based reactors. Both strategies were being applied to the design, construction, and operation of civilian power reactors.

Prevention Strategies

The AEC attempted to reduce the likelihood of accidents (that is, releases of radioactivity from the core) by requiring that reactors be designed conservatively.¹⁵ As in the submarine program, wide margins for error were one principle of conservative design. The material that sheathed the fuel, for example, had to withstand higher temperatures and more corrosive conditions than were expected in actual operation. The number of control rods used to control the rate of chain reaction had to be substantially greater than the number actually needed to shut down the reactor. The pressure vessel in which the core was situated and the pipes through which the coolant flowed had to withstand much higher pressures and temperatures than expected. The coolant pumps had to have the capacity to pump more water for longer than would probably be required, and so on.

The second principle of conservative design was redundancy. If

15. See U.S. Congress, Joint Committee on Atomic Energy, *Hearings of Government Indemnity for Private Licensees and AEC Contractors*, 84th Cong., 2d sess., 1956, pp. 47ff.; *Hearings on Indemnity and Reactor Safety*, 86th Cong., 1st sess., 1959, pp. 236ff., 2d sess., 1960, pp. 20ff.; *Hearings on the Licensing and Regulation of Nuclear Reactors*, pt. 1, 90th Cong., 1st sess., 1967, pp. 62–63, 308ff.; Clifford K. Beck et al., “Reactor Safety, Hazards Evaluation and Inspection,” *Proceedings of the Second U.N. International Conference on the Peaceful Uses of Atomic Energy* (New York: United Nations, 1959), pp. 17ff.

any safety mechanism failed, each reactor would have a backup component or system to perform the necessary function. Thus at least two independent, off-site sources of electrical power had to be available, with completely independent power cables, and each had to be capable of providing all the power required to run the plant. Likewise, at least two independent instruments were required to measure each of the reactor's major operating parameters, such as temperature, pressure, and water level; more than one method had to be provided for injecting control rods into the core; several coolant loops had to be passed through the core, so that if one failed, the others would still be available; and backup pumps and valves had to be provided.

Another tactic for reducing the probability of accidents emerged in the late 1950s. Despite conservative designs, it was assumed that some components and systems would still fail. To cover this possibility, decision makers devised emergency safety systems. Their method was to identify possible malfunctions and sequences of malfunctions that might lead to serious dangers, and then to engineer systems that would operate when such problems occurred.¹⁶

For example, one obvious problem to guard against was a power failure. The safety systems all run on electricity; these include pumps for the coolant system, mechanisms for injecting the control rods, and instruments for measuring reactor conditions. In case both off-site sources of power failed simultaneously, the AEC required as a second line of defense that each nuclear facility be provided with an emergency source of power. This consisted of at least two on-site, diesel generators; each alone had to be capable of providing enough power to run the reactor systems, and the electrical lines for each had to be independent.

Another possibly dangerous malfunction was a loss of coolant. If one or more coolant pipes ruptured and too little coolant reached the core, the fuel might melt and release fission products. To counter this possibility all reactors had to be equipped with emergency core cooling systems. In essence these consisted of alternative sources of water that could be sprayed or pumped into the core if the coolant level fell too low.

16. For one statement of this method, see Joint Committee on Atomic Energy, *Licensing and Regulation of Nuclear Reactors*, Hearings, April 4, 5, 6, 20, and May 3, 1967, 90th Cong., 1st sess., p. 63.

Amelioration Strategies

Because radiation releases might occur despite the multiple prevention strategies, the AEC also required that reactors be designed so as to mitigate the consequences of an accident. Regulators used a variety of approaches in pursuit of this goal.

The most important tactic for mitigating the consequences of reactor accidents was the containment building, intended to prevent radioactive fission products released from the core in an accident from escaping into the environment. According to stipulations by the AEC, the containment building had to be strong enough to withstand "the pressures and temperatures associated with the largest credible energy release" arising from an accident.¹⁷ It also had to be almost gas-tight, so that only very small amounts of fission products could leak into the environment. The precise amount of leakage considered acceptable depended on the distance of the reactor from populated areas. By the late 1950s all reactors had to be designed with containment.

By the early 1960s the containment shields were supplemented by systems for reducing temperatures and pressures after an accident and for washing and filtering out radioactive fission products that might be released into the air within the shield. By such filtering, the small rate of leakage of fission products through the shield could be further reduced.¹⁸ More generally, containment systems became increasingly sophisticated with time.

A second tactic for reducing the consequences of reactor accidents was to build the plants away from populated areas. If fission products were released into the environment, most of the public should be far enough away to escape severe effects. In the early and mid-1950s, the AEC considered this its primary method for mitigating the health effects of accidents. But by the end of the decade the AEC had begun to modify its approach. Reactor sites that had been remote when initially selected were becoming populated, and good sites were scarce in those areas where nuclear power seemed to have the best prospects of becoming commercially viable. Remote siting also led to expensive transmission costs.

17. W. Kenneth Davis and William B. Cottrell, "Containment and Engineered Safety of Nuclear Power Plants," *Proceedings of the Third International Conference on the Peaceful Uses of Atomic Energy*, vol. 13 (New York: United Nations, 1965), p. 367.

18. *Ibid.*

Largely in response to growing industry pressure, a new policy gradually emerged. The suitability of proposed sites would be judged not only on the basis of remoteness, but also on the degree to which "consequences limiting safeguards" had been engineered into the reactor. The revised standard provided that "where unfavorable physical conditions exist, the proposed site may nevertheless be found to be acceptable if the design of the facility includes appropriate and adequate compensating engineering safeguards."¹⁹ Reliance on remote siting thus gave way to reliance on a combination of siting and containment safeguards: the less remote the site, the more extensive the safeguards.

There was however a limit on the extent to which containment could be substituted for distance. In the 1960s some segments of industry and members of Congress began to push for metropolitan siting of reactors. They argued that containment safeguards had become sophisticated enough and reactors safe enough that plants could be built in populated areas without risk to the public. Proposals to build reactors within New York City and Los Angeles were actually submitted. But the Atomic Energy Commission resisted these pressures; it was not willing to substitute completely one form of protection for the other. At least implicitly the regulators continued to use distance from populated areas as a final defense against the potential consequences of accidents, although much smaller distances than in the past.²⁰

The AEC also took into account other characteristics of reactor sites besides remoteness. Three were most important: seismology, because of the possibility that an earthquake might damage the reactor; hydrology, because fission products released in an accident might contaminate ground water and floods could damage the nuclear facility's safety systems; and meteorology, because the distance and direction that fission products released in an accident would travel depended on weather conditions and because tornadoes might damage the reactor. As in the case of remoteness, the AEC permitted the

19. Clifford K. Beck, "U.S. Reactor Experience and Power Reactor Siting," *Proceedings of the Third International Conference on the Peaceful Uses of Atomic Energy*, vol. 11 (New York: United Nations, 1965), p. 355.

20. See for example U.S. Congress, Joint Committee on Atomic Energy, *Hearings on AEC Authorizing Legislation for Fiscal Year 1962*, 87th Cong., 1st sess., 1961, pp. 180–183; Joint Committee on Atomic Energy, *Hearings on Licensing*, pp. 16, 128ff.

use of engineered safeguards to compensate for undesirable characteristics of sites. If for instance the proposed site was in an area prone to tornadoes, a license might still be granted if the reactor designers could demonstrate that the plant would be engineered to withstand them.²¹

One of the most important features of the ameliorative strategy was the procedure by which the AEC evaluated reactor designs and sites. For each proposed reactor, regulators attempted to determine whether it could withstand the "maximum credible accident"; this was defined as a sequence of events that could plausibly lead to a very severe accident. This could occur, for example, from a sudden break in a primary cooling pipe, followed by failure of the emergency cooling system.²²

Once the maximum credible accident had been specified, the AEC attempted to deduce its most extreme consequences. The assumptions were as follows:

The maximum credible accident will release into the [containment] building 100 percent of the [radioactive] noble gases [for example, radon, krypton], 50 percent of the [radioactive] halogens [such as iodine], and one percent of the solids in the fission product inventory; 50 percent of the iodine [one of the most hazardous of the fission products] in the containment vessel will remain available for release to the atmosphere after absorption or adherence to internal surfaces; no credit is taken for washdown or filtering; the release of activity from the building to the environment will take place at the constant rate of 0.1 percent per day; atmospheric dispersion will occur according to the Sutton relationship of wind velocity, atmospheric stability, and diffusion; there will be no shift in wind direction; dispersion will occur under inversion conditions.²³

For a proposed reactor to be approved, the utility company had to demonstrate that the reactor's containment and the distance of the reactor site from populated areas would be sufficient to withstand the consequences of the maximum credible accident. That is, they

21. See for example Joint Committee on Atomic Energy, *Hearings on Indemnity*, pp. 200ff.; see also Joint Committee on Atomic Energy, *Hearings on Licensing*, pp. 193ff.

22. For further detail see S. G. Kingsley, "The Licensing of Nuclear Power Reactors in the United States," *Atomic Energy Law Journal* 7 (1965): 341.

23. *Ibid.*, pp. 339-340.

would be sufficient to prevent the great bulk of the radioactive fission products released from the core from reaching the public.

The Underlying Strategy: Make Reactors Forgiving of Errors

The underlying philosophy of this “defense-in-depth” approach to safety was based on an appreciation of the uncertainty associated with nuclear power. The technology was new. The Atomic Energy Commission was unsure of the performance of the various components and systems, and even more uncertain about complex interactions among systems that might develop in an operating reactor. Under ordinary circumstances, decision makers would have designed reactors to meet the most likely operating conditions, then observed the results. If errors or miscalculations became apparent, they would then have adjusted the design requirements accordingly.

But regulators recognized that the potential consequences of errors in design or operation were too severe for them to proceed in this fashion. Their design philosophy was based on the recognition that there would be errors, that these could lead to severe consequences, and that reactors should therefore be designed to prevent errors from triggering those consequences. And if prevention did not fully succeed, containment and other ameliorative measures would be available to mitigate the effects. That is, nuclear decision makers attempted to make reactors forgiving of errors.

This was analogous to the way a novice goes about learning to fly on a trapeze. Until he or she has mastered the trade, the novice is likely to make mistakes that could result in serious injury. The would-be trapeze artist faces a dilemma similar to that of the reactor developer: on the one hand, some errors are likely; on the other, the consequences of error are potentially severe. The solution is to use devices and tactics that allow the trapeze artist to make the inevitable errors while protecting against the consequences. The performer starts at low heights, perhaps wears some sort of brace with a rope attached, and uses a net to minimize the harm from a fall if all else fails. So it was with reactor regulators. They employed redundancies, wide margins for error, and emergency systems. In case all else failed, they had remote siting and containment. At least in principle, these devices allowed them to make errors without suffering too much from the consequences.

Emphasizing Prevention

These safety strategies and tactics are still employed by the nuclear industry. But the AEC made a crucial shift in emphasis during the mid-1960s, relying much less on containment and much more on prevention.

Impetus for the change came from private enterprise. General Electric and Westinghouse touched off a "great bandwagon market" in the mid-1960s by offering nuclear power plants for sale at prices competitive with those that utilities were paying for coal-fired electricity-generating plants.²⁴ To compete with each other as well as with the smaller firms like Babcock & Wilcox, the two large vendors lowered prices and increased the size of the nuclear plants they were marketing. The result was that American utility companies ordered nearly a hundred light water reactors between 1965 and 1970.

It all began in 1963, when an electric utility company in New Jersey announced that "after thorough consideration of competitive bids from both fossil and nuclear steam system suppliers," it had decided to buy a large boiling water reactor. Two additional light water reactors were ordered by utilities in 1963, seven in 1965, twenty-one in 1966, and twenty-seven in 1967.²⁵

The enormous number of orders from 1965 to 1970 can be attributed in part to unrealistic cost predictions from the AEC and vendors of nuclear power plants. General Electric and Westinghouse had learned from their well-established steam turbine businesses that there were substantial economies of scale to be gained by increasing the size of plants. The utility companies likewise had found they could reduce the cost of generating electricity by building larger coal- and oil-fired generating plants. They reasoned that the same economies of scale should hold for nuclear power. Moreover, years of low inflation and steady growth in demand for electricity had created a sense of complacency about financing the new reactors. Philip Sporn, president of the American Electric Power Company and the only utility executive to criticize the cost estimates of the AEC in the 1960s,

24. The phrase was coined by Philip Sporn. The bandwagon phenomenon is analyzed extensively in Irvin C. Bupp and Jean-Claude Derian, *Light Water: How the Nuclear Dream Dissolved* (New York: Basic Books, 1978; reissued with additional material as *The Failed Promise of Nuclear Power: The Story of Light Water*, 1981), esp. pp. 42-55.

25. Rolph, *Nuclear Power*, pp. 55, 58.

noted that there emerged “a bandwagon effect, with many utilities rushing ahead to order nuclear power plants, often on the basis of only nebulous analysis and frequently because of a desire to get started in the nuclear business.”²⁶

As a consequence, the industry not only scaled up rapidly the number of reactors; even more important, it dramatically increased their size. Reactors ordered in the late 1960s were huge by historical standards, as much as seven times larger than any nuclear plant then in operation. The largest commercial facility operating in 1963 had a capacity of 200 megawatts; only four years later utilities were ordering reactors of 1,200 megawatts. The average capacity of all reactors ordered rose steadily, from 636 megawatts in 1963, to 821 in 1966, to 1,029 in 1969.²⁷

The Shift in Strategy

The increase in reactor sizes had a critical impact on the AEC's safety strategy. By 1967 most analysts had concluded that if the coolant were lost in one of these large nuclear plants and the emergency cooling system failed, containment could no longer be relied on to prevent a substantial release of fission products into the environment.²⁸ For example, a loss of coolant might lead to a China Syndrome,

26. Philip C. Sporn, president, American Electric Power Company, in a letter to the Joint Committee on Atomic Energy, December 28, 1967; repr. in U.S. Congress, Joint Committee on Atomic Energy, *Nuclear Power Economics: 1962 through 1967*, 90th Cong., 2d sess., February 1968, pp. 2–22 (the quotation is from p. 7).

27. Bupp and Derian, *Light Water*, p. 73.

28. Because water is both coolant and moderator in a light water reactor (see Appendix), when such a reactor loses its coolant it also loses its moderator. When the moderator is lost the chain reaction ends, but the core continues to give off heat (though not nearly as much as during the chain reaction—in the first half-minute following the end of the chain reaction, for example, the power of the core is about 7 percent of the peak power during the chain reaction). The heat is generated by the energy released in the radioactive decay of the fission products produced during the chain reaction. Normally, this “decay heat” is removed by the reactor coolant. Without coolant it cannot be removed, and if it cannot it will melt the material in which the fuel is enclosed and eventually the fuel itself. Once the fuel begins to melt, serious emissions of radioactive fission products are possible.

The scale-up to more powerful reactors was significant because of this problem of decay heat. The more powerful the reactor, the greater the amount of fission products during operation, and consequently the greater the amount of decay heat. And the greater the amount of decay heat, the more severe the heat removal problem in an accident involving loss of coolant. “To gain an appreciation of the magnitude of the problem, it might be noted that the decay heat production from a large reactor, such

in which the molten core would melt through the reactor vessel and then through the floor of the containment building. Or, once the core melted, it might somehow come in contact with water and set off a steam explosion powerful enough to breach containment. A core melt would not inevitably lead to failure of containment, for the containment building would withstand the effects of some core melts, even in large plants. But the maximum credible accident might breach containment.

Nuclear engineers were unable to find economically feasible ways to strengthen containment sufficiently. Double containment shields were considered and rejected. Also proposed was a device to catch the reactor core if it melted through the reactor vessel. But neither these nor other proposals provided enough assurance of limiting the worst credible effects of core melts in large reactors.²⁹

The AEC therefore decided to enhance and place much greater reliance on the prevention strategy: nuclear plants would have to be designed so that errors in design, construction, and operation never triggered significant releases of fission products from the core.³⁰ In effect, the AEC concluded that if it could no longer guarantee containment, it would have to prevent all the conceivable sequences of events that might lead to a breach of containment. (Containment is still used to guard against small accidents, for which it is believed to be effective.)

Enhanced prevention in large reactors was based on the same approaches that had been employed in the smaller reactors, but now these approaches were applied even more stringently. This was most apparent in changes required for emergency core cooling systems. Because loss of coolant was the main threat to containment, many of the changes were directed at ensuring a supply of coolant under all circumstances. Before 1966 emergency cooling systems had been in-

as proposed for Browns Ferry [ordered in 1966], begins to approach a level comparable to the original full load power level of the Shippingport Reactor." Joint Committee on Atomic Energy, *Hearings on Licensing*, p. 95.

29. See especially David Okrent, *Nuclear Reactor Safety: On the History of the Regulatory Process* (Madison: University of Wisconsin Press, 1981), chap. 8.

30. See for example U.S. Congress, Joint Committee on Atomic Energy, *Hearings on Nuclear Reactor Safety*, 93d Cong., 1st sess., 1973, pp. 34ff. More generally see U.S. Congress, Joint Committee on Atomic Energy, *Hearings on AEC Licensing Procedure and Related Legislation*, pts. 1, 2, 92d Cong., 1st sess., 1971; U.S. Atomic Energy Commission, *The Safety of Nuclear Power Reactors and Related Facilities*, Draft, WASH-1250 (Washington: U.S. Government Printing Office, 1973).

tended only for small problems. Had a major pipe in the primary system ruptured, the emergency cooling system could not have replaced the coolant quickly enough to prevent at least some melting of fuel. This was considered acceptable for smaller reactors, because the fission products released by such melting were expected to be contained.

In 1966 the AEC ordered substantial upgrading in the capacity of emergency cooling systems. The new systems were designed to protect against all possible pipe breaks in the primary coolant system. New protections were also added to protect the safety systems themselves, for a violent release of steam from a ruptured pipe could hurl fragments of metal that might disable some of the emergency equipment. And the AEC ordered measures to ensure a supply of electricity to the emergency systems.³¹

New redundancies also were added. Thus pressurized light water reactors were equipped with two completely independent systems for providing emergency cooling. One was a coolant injection system, which pumped water into the core in the event of a loss of coolant. If the coolant were lost through a large break, a set of low pressure pumps would be used; if it were lost through a small break, in which case there would still be a good deal of pressure within the core, high pressure pumps would be used. Each set of pumps itself was made up of redundant sets of pumps, so that if one set failed another would still be available to perform the necessary functions.³²

The second emergency system was a passive one, composed of large tanks of water. In the event of a major break in a crucial pipe, a drop in water pressure in the core would cause the tanks to discharge their contents very rapidly into the reactor vessel.³³ This system also was designed redundantly, with more water tanks than would actually be needed to cool the core.³⁴

Thus the emergency core cooling system was designed to back up the ordinary one, and the emergency system itself had two methods for performing its intended function; each of these in turn had

31. William B. Cottrell, "The ECCS Rule-making Hearing," *Atomic Energy Law Journal* 16 (1975): 350–415, esp. pp. 353ff.

32. U.S. Nuclear Regulatory Commission, *Reactor Safety Study*, WASH-1400 (Washington: U.S. Government Printing Office, 1975), app. 9, p. 37.

33. Cottrell, "ECCS Hearing," p. 354.

34. Nuclear Regulatory Commission, *Reactor Safety Study*, app. 9, p. 37.

provisions for backup in case something malfunctioned. In addition, the new emergency cooling systems were designed with wide margins for error. In the late 1960s and early 1970s, as a result of a series of controversies, these margins were repeatedly expanded.³⁵

Because of perceived uranium shortages, the desire for nuclear submarines, and a commitment to low-cost power production through private enterprise, policy makers placed little weight on considerations of safety in their selections of reactor types (see chapters 2 and 3). But safety was nonetheless a major concern in the formative years of nuclear power, and a subject of deliberate, intensive strategies that evolved over the course of two decades.

The overall approach was one of add-on, or engineered, safety. Once a reactor was selected for development for reasons other than safety, it had to be designed and engineered into a safe reactor. By the early 1960s this approach to safety had four basic components, two of which were aimed at preventing accidents:

- Redundancies and wide error margins to prevent errors from triggering emergencies;
- Emergency systems to intervene if serious problems arose.

The two other components were aimed at making accidents less serious if they did occur:

- Containment to prevent fission products released in an accident from entering the environment;
- Remote siting to dilute radioactivity that might escape containment before it reached major population centers.

As private industry began to deploy larger reactors in less remote sites, however, the Atomic Energy Commission deemphasized the third and fourth components. The AEC could have stuck with its original balance between preventing and minimizing accidents by denying construction licenses for the huge reactors, but it did not. As utilities throughout the country began to order reactors of 1,000 megawatts or more, the AEC chose to shift away from the balance and rely increasingly on complete prevention of accidents. This proved to be a fateful decision.

35. For a partial list of these margins see Atomic Energy Commission, *Safety of Nuclear Power Reactors*, pp. 5–9.

PART II

Interpretation

CHAPTER FIVE

Turning Point The Scale-up of the Mid-1960s

The euphoria of the great bandwagon market died quickly. Even as it was reaching its peak the environmental protest movement was emerging, and nuclear power soon became one of the primary targets. Local protests quickly coalesced into a nationwide movement, and by the early 1970s the nuclear landscape had changed remarkably. An important judicial decision required the AEC to relicense all sixty reactors then operating or under construction.¹ Questions about the adequacy of emergency core cooling systems and other safety features were soon carried into the political realm by such antinuclear groups as the Union of Concerned Scientists.² The Atomic Energy Commission was dismantled and replaced by the Nuclear Regulatory Com-

1. Calvert Cliffs Coordinating Committee v. AEC, 449 F.2d 1109 (1971); discussed in Frank G. Dawson, *Nuclear Power: Development and Management of a Technology* (Seattle: University of Washington Press, 1976), pp. 198–203. For a good overview of opposition to nuclear power during the late 1960s and early 1970s see Steven L. Del Sesto, *Science, Politics, and Controversy: Civilian Nuclear Power in the United States, 1946–1974* (Boulder: Westview, 1979), chaps. 5–7.

2. One of the early partisan analyses in the controversy over emergency core cooling systems is Daniel F. Ford, Henry W. Kendall, and John J. MacKenzie, "A Critique of the AEC's Interim Criteria for Emergency Core-cooling Systems," *Nuclear News* 15 (January 1972): 28–35. A recent overview is Joseph L. Campbell, *Collapse of an Industry: Nuclear Power and the Contradictions of U.S. Policy* (Ithaca: Cornell University Press, 1988), pp. 50–72.

mission, which took over the function of regulating the industry, and the Energy Research and Development Administration (predecessor to the Department of Energy), which took over the responsibility for reactor development.³ The Joint Committee on Atomic Energy was abolished, and more than a dozen committees and subcommittees in the House and Senate claimed jurisdiction over various aspects of nuclear power.⁴ An analysis of reactor safety known as the Rasmussen Report, intended to put an end to the growing debate over safety, spurred further controversy.⁵ So too did a potentially catastrophic fire at the Browns Ferry reactor in Alabama, which was started by a maintenance worker using a candle instead of a flashlight.⁶

Meanwhile, the regulatory process was rapidly unraveling, and the now familiar problem of regulatory delay already becoming apparent. Between 1966 and 1970 the average time required merely to gain a construction permit tripled, to almost three and a half years.⁷ And the economics of nuclear power, which a few years earlier had looked so promising, were beginning to sour. Utilities began canceling orders for nuclear plants in the early 1970s; there were five cancellations in 1972 and sixteen more in the next two years. Initially these were more than balanced by new orders, but utilities purchased no reactors in 1975, and by 1976 it was becoming apparent that the American nuclear industry was in trouble.⁸

The problems would only get worse. Regulatory controversies

3. Robert Gillette, "Nuclear Safety (III): Critics Charge Conflict of Interest," *Science* 177 (1972): 970-975.

4. Harold P. Green and Alan Rosenthal, *Government of the Atom: The Integration of Powers* (New York: Atherton, 1963); Edward J. Woodhouse, "The Politics of Nuclear Waste Management" in Charles A. Walker et al., eds., *Too Hot to Handle? Social and Policy Issues in the Management of Radioactive Wastes* (New Haven and London: Yale University Press, 1983), pp. 151-183.

5. U.S. Nuclear Regulatory Commission, *Reactor Safety Study*, WASH-1400 (Washington: U.S. Government Printing Office, 1975).

6. David Okrent, *Nuclear Reactor Safety: On the History of the Regulatory Process* (Madison: University of Wisconsin Press, 1981), pp. 220, 231.

7. On licensing delays see among many other sources B. R. Weingast, "Congress, Regulation, and the Decline of Nuclear Power," *Public Policy* 28 (1980): 243, as well as Irvin C. Bupp and Jean-Claude Derian, *Light Water: How the Nuclear Dream Dissolved* (New York: Basic Books, 1978; reissued with additional material as *The Failed Promise of Nuclear Power: The Story of Light Water*, 1981); Steven L. Del Sesto, *Science, Politics, and Controversy: Civilian Nuclear Power in the United States, 1946-1974* (Boulder: Westview, 1979), pp. 96-100; E. S. Rolph, *Nuclear Power and the Public Safety* (Lexington, Mass.: Lexington Books, 1979).

8. OTA, 1984, p. 29.

continued, delays got longer, and requirements for back-fitting existing plants to meet more stringent standards were added one on top of the other. In the first half of the decade public support for nuclear power in general had remained relatively high, but a growing number of people were becoming uneasy about living in the same neighborhood as a nuclear plant. This trend gradually accelerated, and in 1978 there was a sharp upturn in opposition.⁹ The pace of cancellations continued unabated throughout the second half of the decade, and no new plants were ordered after 1978.

Then came Three Mile Island, and in its wake the realization and admission that the American nuclear enterprise was seriously off course. A spate of studies after the accident confirmed what only the industry's harshest critics had previously perceived: that the regulatory system was unworkable and the industry in disarray.¹⁰ By the early 1980s public opinion was nearly the mirror image of what it had been ten years earlier: roughly 60 percent of those polled opposed new construction, and only 30 percent favored it.¹¹ Leading executives in utilities were admitting at least in private that nuclear power was no longer viable and those in the supply industry were quietly looking for ways to cut their losses and perhaps even get out of the business altogether.¹² With the exception of plants already in operation or nearing completion (and the firms servicing them), the nuclear enterprise was for all intents and purposes dead. If this was not entirely clear to those in and around the industry who were still promoting "regulatory reform" as a solution to the industry's ills, it became unmistakable after the accident at Chernobyl.

9. Ibid., pp. 211ff.

10. See for example President's Commission on the Accident at Three Mile Island, *The Need for Change: The Legacy of TMI* (Washington: U.S. Government Printing Office, 1979); summarized and evaluated in David Okrent and Dade W. Moeller, "Implications for Reactor Safety of the Accident at Three Mile Island, Unit 2," *Annual Review of Energy*, vol. 6, ed. Jack Hollander, Melvin K. Simmons, and D. Wood (Palo Alto: Annual Reviews, 1981). See also Nuclear Regulatory Commission, Special Inquiry Group, *Three Mile Island: A Report to the Commission and to the Public* (Washington: U.S. Government Printing Office, 1980).

11. Robert C. Mitchell, "Public Responses to a Major Failure of a Controversial Technology," in David L. Sills et al., eds., *Accident at Three Mile Island: The Human Dimensions* (Boulder: Westview, 1982), pp. 21–38; William R. Freudenberg and Eugene A. Rosa, eds., *Public Reactions to Nuclear Power: Are There Critical Masses?* (Boulder: Westview, 1984).

12. Graham Allison et al., "Governance of Nuclear Power" (Washington: President's Nuclear Oversight Committee, 1981).

This downward spiral of events was as irrevocable as it was rapid. One difficulty fueled the next, and the rate at which this happened seemed to accelerate. Yet as varied and complex as these difficulties became, one set of decisions stands out as the catalyst, the central cause of the demise of American nuclear power: the rapid scale-up in the number and size of reactors and the resulting shift in safety strategy.

Unprovable Safety

The scale-up in reactor sizes forced the AEC to change its reactor safety strategy (see chapter 4). Because containment could not be relied on to safeguard the public from especially severe accidents in large reactors, the AEC set out to prevent all such accidents. The primary approach was to upgrade emergency systems, add additional redundancies, and widen the margins for error. These changes probably did reduce the likelihood and severity of accidents. Paradoxically, however, the shift in strategy had a crucial and unexpected effect: it made it impossible to demonstrate that reactors were acceptably safe.

Relying on prevention of all accidents as a last line of defense is a much more complicated process than relying on containment and remote siting. Prevention demands that reactor designers and regulators anticipate every possible malfunction and sequence of malfunctions that could trigger a melting of the core, foresee every possible condition that could result from each of the many conceivable malfunctions, and design the reactor so that it can respond to and withstand this host of possible malfunctions and resulting conditions. By contrast, according to the earlier approach the primary task was to define the worst credible effects of a core melt and design containment and remote siting accordingly. This was subject to some disagreement, of course, and certainly reactor designers and regulators attempted to anticipate possible malfunctions. But the essence of this earlier strategy was to limit the consequences of serious accidents rather than rely entirely on preventing them. Attention could be focused much more narrowly: how bad could the maximum credible accident be, and what would it take to withstand it? Accordingly, the range of debate was relatively constrained.

The shift to prevention expanded the realm of debate almost in-

finitely. Now it became necessary to envision all the possible events and sequences of events, consequences, and consequences of consequences that could plausibly lead to a meltdown. These range from operator error to tornadoes and floods, acts of terrorism, power failures, material failures, component failures, emergency system failures, maintenance errors, construction errors—the list is virtually endless. And the seemingly endless nature of the list was precisely the problem. The reliance on prevention created a regulatory, political, and analytical morass; it put nuclear decision makers in the position of having to demonstrate that they had anticipated everything that could go wrong in a reactor.

The Change in Climate

In an earlier time, when trust in government and faith in science and business were high, most people would probably have gone along with the large majority of nuclear experts who considered reactors safe enough. Ironically, though, the shift to a strategy requiring greater public trust came at the very time that the political culture was becoming less deferential to government, business, and the status quo. The scale-up and shift in strategy came at the dawn of an age in which nuclear politics would become the province of dissident scientists, citizens' groups, courts, overlapping congressional committees, the news media, and others.

More generally, public attitudes were changing markedly, with many people losing their faith in government and other social institutions. In 1964, for example, only 22 percent of those surveyed in a national poll agreed with the statement: "You cannot trust government to do right most of the time." This proportion had doubled by 1970, and by 1980 risen to an astonishing 70 percent.¹³ Trust in business declined just as sharply. In 1965 two-thirds of those interviewed held very favorable or mostly favorable attitudes toward the automobile, aluminum, chemical, electrical, food, oil, steel, and tire and rubber industries; by 1977 only one-third did. Attitudes toward particular major corporations, such as Sears, du Pont, Exxon, and AT&T, likewise declined precipitously.

Most of these changes in public attitudes occurred between 1965

13. Unless otherwise noted, the opinion data in this section are from Seymour M. Lipset and William Schneider, *The Confidence Gap: Business, Labor, and Government in the Public Mind* (New York: Free Press, 1983), pp. 13–40.

and 1972, which is exactly when commercial nuclear power was becoming politically visible—and vulnerable. Moreover, other changes were occurring simultaneously. The civil rights and antiwar movements were front-page news throughout the mid- and late 1960s. Almost overnight, the public became strongly environmentalist. And the AEC and other political institutions that had governed nuclear power for a quarter-century were beginning to be viewed with suspicion, partly because they had become identified as promoters of nuclear power, but just as much because they seemed to be trying to keep a lid on problems instead of airing them openly.¹⁴

In this kind of political climate, so different from the trusting one of the 1950s and early 1960s, safety would have to be proven, not taken on faith. But how could nuclear designers demonstrate conclusively that something unanticipated would not occur? Not surprisingly, the requirement that all accidents be prevented gave birth to what might be called the “What if?” syndrome. In the years following the scale-up and shift in strategy, a series of controversies rocked the nuclear regulatory system. At the root of each was the possibility that some pathway to an accident, some critical sequence of malfunctions, had not been protected against:

- What if the pressure vessel failed?
- What if the emergency core cooling system did not flood the core as quickly as anticipated?
- What if through some unanticipated interconnection, several supposedly independent safety systems failed simultaneously?
- What if the operating temperature rose and both the control rods and pumps that circulate coolant into the reactor failed?
- What if the turbine failed and pieces of it were hurled like missiles?
- What if pipes cracked as a result of stress corrosion?

Such questions could be asked ad infinitum. Reactors are so complex that it was possible for opponents to postulate numerous combinations of events that could conceivably trigger a core melt. The probabilities might be very low, but unforeseen events could not be

14. A good treatment of the phenomenon, albeit a partisan one, is Daniel Ford, *The Cult of the Atom: The Secret Papers of the Atomic Energy Commission* (New York: Simon and Schuster, 1982).

ruled out entirely. Nor was there any way to dispel lingering doubts about whether the capacities of the emergency systems had been properly estimated, or whether these systems might fail in ways that had not been examined. Both in practice and in principle, it was impossible to prove that the unanticipated would not occur.

The Inescapable Trap

Nuclear advocates and regulators never fully comprehended the trap they had created for themselves with the shift in strategy. Faced with repeated challenges, however, they did make several attempts to overcome the problem of how to demonstrate safety. The most notable one came in the early 1970s, when the AEC commissioned an assessment of reactor safety that later gained some notoriety as the Rasmussen Report.¹⁵

The Rasmussen Report, or Reactor Safety Study, was based on an analytic technique known as fault tree analysis. It attempts to identify all the possible sequences of errors and malfunctions that could lead to serious accidents and estimate the probability of each error and malfunction. Based on these calculations, estimates of the likelihood of each sequence of malfunctions are made, which are in turn the basis for estimating the overall likelihood of a serious accident.

The significance of this form of analysis is that it offers a method for calculating the likelihood of events (that is, serious accidents) that have never or rarely occurred. The key is to focus on particular errors and malfunctions that could lead to an accident rather than on the accident itself. Unlike the accident, many of the individual errors and malfunctions are relatively common—not only in reactors, but in a variety of industrial enterprises. For example, the nuclear industry has decades of experience with control rod mechanisms that regulate the rate of chain reaction, so it is possible to develop fairly reliable estimates of how often the mechanism will fail. Similarly, it is possible to estimate the likelihood of power failures, pump failures, pipe failures, and so on.

Using this approach, the Rasmussen Report reached a rather optimistic conclusion about reactor safety. Calculations showed that nuclear reactors posed much lower risks than other technologies widely

15. Nuclear Regulatory Commission, *Reactor Safety Study*.

accepted by the public, such as dams and airplanes. And even though the report calculated that the worst plausible reactor accident would lead to 3,300 early fatalities, 1,500 latent cancer fatalities, and 45,000 illnesses, it estimated the probability of such a severe accident to be one in a billion per reactor per year.¹⁶

Nuclear advocates were surprised and disappointed when this conclusion did nothing to allay the growing controversy and concerns about reactor safety. If anything, it exacerbated the problem by bringing the underlying dilemma to the surface. A special committee of the prestigious and nonpartisan American Physical Society criticized the methodology and conclusions of the Rasmussen Report, and this helped to fuel criticisms by the Union of Concerned Scientists and other nuclear opponents.¹⁷ The basic objection was that fault tree analysis suffered from the same difficulties that had confronted the AEC since the scale-up and shift in safety strategy, and that had prompted commissioning of the Rasmussen study in the first place:

- What if analysis failed to identify all the possible sequences of malfunctions that could lead to an accident?
- What if safety systems presumed to be independent are actually vulnerable to common events?
- What if the probabilities of inherently uncertain errors—such as mistakes by those operating a reactor—have been underestimated?

Prevention required anticipating all that could go wrong. But how could nuclear decision makers know that they had really protected against all the possibilities? And how could they possibly prove it to increasingly skeptical environmental groups, journalists, and ordinary citizens?

If analysis cannot be used to prove the safety of reactors, what about the actual safety record that has been achieved? The American nuclear industry is generally considered to have an outstanding record. As in most other industries, there have been numerous malfunctions, many problems with sloppy maintenance and poor management, workers asleep on the job, and even a few serious accidents. But these failures have not actually caused any known injuries or

16. *Ibid.*, executive summary, p. 83.

17. Study Group on Light Water Reactor Safety, "Report to the APS by the Study Group on Light Water Reactor Safety," *Reviews of Modern Physics* 47, supp. 1 (1975).

deaths among the public. As pronuclear commentators point out, even the accident at Three Mile Island killed no one. But the sterling safety record does not provide a way out of the regulators' dilemma; ironically, the reason why it does not can be traced to the low probability of a serious reactor accident.

The difficulty can be illustrated by the other major effort to deal conclusively with the proof-of-safety problem. In the early 1980s the Nuclear Regulatory Commission set out to establish a safety goal for nuclear reactors—that is, a level of safety that would make a given reactor “safe enough,” or acceptable to society. One part of this goal required that the probability of an accident causing a hundred deaths be no higher than one in a million per reactor per year. In other words, such an accident would occur on average about once in ten thousand years in an industry with a hundred reactors. In the NRC's judgment, such a low probability would be deemed an acceptable risk by the public, and this might help to ease public concerns about reactor safety.

We suspect that the NRC's judgment was correct: most people probably would find that level of safety acceptable. The problem was that there was no way to demonstrate that reactors really were that safe. How was the NRC to prove that serious accidents would be so rare, other than to wait for thousands of years? The NRC and nuclear advocates could not win: they could be proven wrong by an accident that occurred sooner than forecast, but at least for several thousand years they could not prove themselves correct.¹⁸

The Effect on Public Perceptions

What effect did the scale-up and shift in strategy have on the overall risks of reactor accidents? Not much, the advocates could claim. True, a serious accident in a large reactor would have more severe consequences, but the probability of such an accident was reduced by the enhanced safety measures taken after 1965. Because professional risk assessors define risk as the probability of an accident multiplied by its severity, the combination of lower probability and greater severity

18. For further detail on the safety goal and its shortcomings see Joseph G. Morone and Edward J. Woodhouse, *Averting Catastrophe: Strategies for Regulating Risky Technologies* (Berkeley: University of California Press, 1986), p. 46.

may have left overall risk at roughly the same level as before the scale-up and shift in strategy.¹⁹

But the public tends not to view risks in such an analytic fashion. Since the 1970s social psychologists have been studying public perceptions of nuclear power, going deeper than simply asking whether people were for it or against it. Their goal has been to understand the underlying structure of attitudes, and the motivating factors that lead to attitudes. The basic conclusion of this research is that people's perceptions of risk are not shaped primarily by the annual fatality and injury estimates that preoccupy professional risk assessors; instead, most people are guided largely by the character of the hazard.²⁰ Specific findings include the following:

- Familiar hazards are more acceptable than unfamiliar ones;
- Voluntary risks tend to be accepted readily, whereas involuntary risks are resisted;
- Where an individual has some personal control, as in driving an automobile, the risk will be more acceptable than where one's life is entirely in someone else's hands;
- Risks are judged in relation to their perceived benefits;
- One of the most influential characteristics of a hazard is the potential it poses for catastrophe, for killing hundreds or thousands of people at once.

Nuclear power scores worse on these five criteria than virtually any other technology: it is unfamiliar, involuntary, and not under personal control, with low perceived benefits and a dramatic potential for catastrophe.

Of these characteristics, the one that seems to contribute most to public perceptions of nuclear power is its potential for catastrophe. One study of some ninety risky technologies and activities, ranging from food coloring to football to nuclear power, found that public perceptions of risk are closely related to the degree to which the risk is viewed with "dread"—that is, associated with fatal consequences

19. For intelligent examples of this form of professional risk assessment see Edmund A. C. Crouch and Richard Wilson, *Risk/Benefit Analysis* (Cambridge, Mass.: Ballinger, 1982); Richard C. Schwing and Walter A. Albers, eds., *Societal Risk Assessment: How Safe Is Safe Enough?* (New York and London: Plenum, 1980).

20. Baruch Fischhoff et al., *Acceptable Risk* (New York: Cambridge University Press, 1984).

for large numbers of people. Nuclear power was viewed with more dread than any of the other technologies and activities except nuclear weapons and warfare, and the difference there was slight.²¹ One social psychologist noted: "The public is much affected in its perception of the seriousness of a hazard by the potential size of a single catastrophe. There is little doubt that this is one of the most important factors to account for the public's assessment of risk from nuclear power generation. They accept that an accident is highly unlikely but they perceive, rightly or wrongly, that it might be devastatingly serious if it occurred."²²

The social psychologists attempt to explain this finding by pointing to certain patterns in human reasoning and judgment.²³ But the important point for us is simple: the strictly analytic view of risk is just about irrelevant to the politics and public perceptions of nuclear power. Because of the way most people think about risk, the scale-up and shift in strategy were extraordinarily consequential; they virtually guaranteed the public rejection of nuclear power.

This point is central to understanding the nuclear power experience. To allay public fears, nuclear decision makers needed to make obvious that there was no significant catastrophic potential; the original strategies of containment, remote siting, and small reactors essentially accomplished this. With the shift in safety strategy, nuclear policy makers went in exactly the opposite direction. Large reactors with safety systems oriented toward prevention may perform satisfactorily, but there is no way to prove that they will. Given the magnitude of the potential consequences of reactor accidents and the importance of the "dread" factor in shaping public perceptions, this makes many people profoundly uneasy. Once reactors were scaled up and the safety emphasis shifted to prevention, each new incident at a nuclear plant, no matter how harmless, reinforced the commonsense view that it was simply not possible to anticipate fully the unanticipated, which in turn heightened the dread factor. In practice and

21. P. Slovic, B. Fischhoff, and S. Lichtenstein, "Perceived Risk: Psychological Factors and Social Implications," *Proceedings of the Royal Society of London*, ser. A, vol. 376, Mathematical and Physical Sciences (1981), pp. 17–34.

22. T. R. Lee, "Perception of Risk," *Proceedings of the Royal Society of London*, ser. A, vol. 376, Mathematical and Physical Sciences (1981), p. 15.

23. See for example A. Tversky and D. Kahneman, "The Framing of Decisions and the Rationality of Choice," *Science* 211 (1981): 453–458.

principle, it was impossible to reassure the public that no hidden paths to the much feared catastrophe lay in the future.

Then came Three Mile Island.

Three Mile Island

Public support for nuclear power began to decline by the mid-1970s, but it was not until the accident at Three Mile Island that support fell below 50 percent.²⁴ The accident that occurred outside Harrisburg, Pennsylvania, in March 1979 was caused by a tragicomedy of errors.²⁵ Maintenance errors included shut valves that prevented a backup system from pumping water into the secondary loop, and a stuck pressure relief valve that allowed water from the primary loop to escape and pressure in the loop to fall. Errors by those operating the reactor included shutting down the emergency cooling system, removing water from the primary loop, and shutting down the pumps in the primary loop. And there was at least once design error: instrumentation that led operators to believe the reactor was full of water when in fact it badly needed additional coolant. A reactor control panel that was difficult to use and computer diagnostics that ran hours behind events might be considered additional design errors.

Despite this rash of errors, the accident caused virtually no harm to public health. According to the Kemeny Commission, appointed by President Carter to investigate the accident, the effects of the released radioactivity were "negligible."²⁶ More important, the analysis concluded that owing to the forgiving nature of reactor design, if the accident had gone on for several days rather than several hours, reactor operators would have had many more opportunities to get emergency coolant into the core. Water could have been restored by a variety of mechanisms: a high-pressure water injection system, a core flooding system, a containment spray, and containment coolers.²⁷ In-

24. Mitchell, "Public Responses"; Freudenberg and Rosa, *Public Reactions to Nuclear Power*.

25. For further details see Morone and Woodhouse, *Averting Catastrophe*, pp. 48–55 and sources cited therein.

26. See President's Commission on the Accident at Three Mile Island, *The Need for Change*. For various social interpretations of the accident see Sills et al., *Accident at Three Mile Island*, originally prepared for the President's Commission on the Accident at Three Mile Island.

27. Robert J. Breen, "Defense-in-Depth Approach to Safety in Light of the Three Mile Island Accident," *Nuclear Safety* 22 (1981): 561–569.

deed, the commission found that even if coolant had never been restored and the core had melted through the reactor vessel, the core would probably have solidified on the floor of the containment building. If it did not and the core had melted through the floor (a China Syndrome), the containment building and hard rock under it probably would have held in most of the radioactivity.²⁸

Ironically, even though Three Mile Island badly damaged the credibility of the nuclear industry, it can thus be interpreted as a vindication of the underlying theory of reactor safety that had evolved over the past thirty years. As we have seen, according to this theory reactors were to be made forgiving of errors through combinations of redundancies, wide margins for error, emergency systems, and ameliorative strategies. If nothing else, Three Mile Island was a vivid demonstration of the intelligence of defense in depth in reactor design. Engineered safety performed more or less as it was designed to perform, even under stern challenge.

But Three Mile Island also highlighted the difficulties of relying primarily on prevention. It brought into sharp focus the problem that the nuclear enterprise has been struggling against since the fateful scale-up and shift in strategy: there was no way that nuclear decision makers could envision all the events and sequences of events that could lead to a core melt and consequent release of radiation.

The accident revealed two broad classes of potential problems to which the nuclear community had given insufficient attention. First, the Atomic Energy Commission and its successor agencies had focused mainly on design errors, as opposed to errors that might be made by plant operators and maintenance engineers. Yet human errors at Three Mile Island contributed significantly to the accident. Also previously underemphasized were minor malfunctions, such as the stuck pressure relief valve that caused so much difficulty. Before the accident, regulators had directed most of their attention to severe malfunctions, such as major failures in the cooling system. They assumed that protections taken against these would also be capable of dealing with lesser problems. But Three Mile Island showed otherwise: even minor malfunctions could potentially lead to meltdowns.

Therefore, although engineered safety did protect the public in this case, Three Mile Island badly damaged the credibility of the

28. President's Commission on Three Mile Island, *Need for Change*, p. 56.

nuclear enterprise. It vividly and starkly demonstrated that unanticipated things could go wrong in a reactor. It added new validity to the "What if?" syndrome, to the often unspoken public concern that something unexpected might go wrong and somehow unleash the catastrophic potential. In terms of nuclear power's political safety, TMI was a disaster. For the lesson the news media and public learned from it was based not on what actually happened (which is to say very little), but on what might have happened. Unanticipated mistakes were made, design flaws exacerbated the problem, unforeseen damage to the reactor core resulted, and public officials and regulatory agencies showed themselves to be confused and uncertain. All this made the possibility of a catastrophe much more real to the public than it had ever seemed before.

Chernobyl

The nuclear accident at Chernobyl in April 1986 dwarfed all previous problems with civilian nuclear power plants. The reactor released nearly 100 million curies of radioactivity, compared with 15 curies at Three Mile Island. The accident occurred because of a series of problems:

- A test was being conducted under the jurisdiction of electrical experts not thoroughly familiar with nuclear safety;
- Operators failed to stabilize the reactor at 20 percent of power, operating it at just 6 or 7 percent, in spite of rules prohibiting low-power operations;
- The operators withdrew all but six of 215 control rods from the core, although at least thirty are required according to the operating manual for the Chernobyl reactors;
- Operators turned off the automatic equipment designed to shut down and cool the reactor in an emergency;
- Operators kept the unit running in spite of a computer printout warning several minutes before the accident that the reactor was in serious danger and should be shut down immediately.²⁹

Soviet scientists and officials who investigated the accident con-

29. Stuart Diamond, "Reactor Fallout Is Said to Match Past World Total," *New York Times*, September 23, 1986, sec. A, p. 1.

cluded that the operators had lost their "sense of vigilance towards safety."³⁰ One author of the report of the International Nuclear Safety Advisory Group on the Chernobyl accident said that "the operators got swelled heads" because the reactor had enjoyed the best operating record of any reactor in the Soviet Union. As a result, "they thought they could do anything to this reactor."³¹

The accident revealed four differences between civilian reactors in the United States and the one at Chernobyl. First, it was much easier for the Soviet operators to override the automatic safety mechanisms; had they not done so, the reactor would have shut itself down before the meltdown. A second design deficiency became apparent when reactor operators discovered that there was a problem, by which point they had only four seconds to get control rods into the core to stop the chain reaction. With the power-operated control rods used on most light water reactors this would have been enough time, but it was not enough for the Soviet reactor, which relied on gravity for inserting the rods.

Third, the graphite reactor suffered a runaway reaction that could not have happened in a light water reactor; power increased some 1,400 times in five seconds, to more than one hundred times the reactor's normal capacity at full power. In contrast, the total power surge theoretically possible in light water reactors is only 2.2 times normal full power.³² Boiling water reactors were initially rejected for development because they seemed to pose a threat of a runaway reaction (see chapter 3). Through experiments, however, American reactor designers found that boiling water reactors could be made self-stabilizing, and all civilian light water reactors have been designed so as to slow down the chain reaction as the reactor core heats up. If the Soviet reactor had used such a design feature, the reactor's operators would have had time to insert the control rods and prevent the accident.

Fourth, though the Soviet reactor had some containment protec-

30. Harold R. Denton et al., "Report on the IAEA Meeting on the Chernobyl Accident" (report to the Nuclear Regulatory Commission, September 3, 1986), p. 1.

31. Herbert J. C. Kouts, head of the Department of Nuclear Energy, Brookhaven National Laboratory, oral presentation to the American Nuclear Society symposium, Saratoga Springs, N.Y., September 1986; quoted in *New York Times*, September 23, 1986, sec. A, p. 1.

32. This is for boiling water reactors; power surges in pressurized water reactors are even less of a problem.

tions, it did not have a full containment shield like those of most Western nations, designed to withstand an explosion and still keep the radioactivity from being released into the environment. Whether such containment would have been sufficient to withstand an accident like that at Chernobyl is, however, debatable. At least one prominent analyst has argued that it would have been,³³ but a study by the International Nuclear Safety Advisory Group could not determine whether the Soviet explosion would have been contained in an American reactor.³⁴

In a way, the Soviet accident further verifies the wisdom of the American approach to nuclear safety. Had Chernobyl's reactor been designed with the multiple redundancies and wide error margins of American light water reactors, the accident might not have happened, and if an accident of Chernobyl's magnitude had occurred in a light water reactor with containment, much of the radioactivity might have been contained rather than released to the environment.

From a technical viewpoint, Chernobyl can be interpreted in much the same way as Three Mile Island: as further proof of the sensibility of engineered safety. Secondly, by providing new information about accidents, Chernobyl should lead to further improvements in heretofore underemphasized aspects of reactor safety. The Harvard physicist Richard Wilson summarized the impact of Chernobyl as follows: "The U.S. situation can be compared to that of a careful driver with a well-built and inspected car who passes a wrecked car on the highway when out of state. He notes that in his state, the damaged car could not have been on the road, and he is unsure of the competence of the car's driver. Nonetheless, the careful driver slows down a little, reconsiders the safety of his own car, and resolves to keep his seat belt buckled."³⁵

On the other hand, Chernobyl has had a devastating impact on public perceptions of nuclear risks. Where Three Mile Island was a reminder that something might happen, at Chernobyl something did happen. The potential for catastrophe that underlay the public rejection of nuclear power was fully realized.

The effect on public polls was predictable. Even before Chernobyl

33. Richard Wilson, "Chernobyl: Assessing the Accident," *Issues in Science and Technology* 3 (Fall 1986): 21-29; the quotation is from p. 26.

34. *New York Times*, September 23, 1986, sec. A, p. 1.

35. Wilson, "Chernobyl," p. 22.

byl, in early 1986 only a third of those interviewed in the United States considered nuclear energy a desirable source for additional exploitation. After the accident, some 78 percent expressed opposition to building additional nuclear plants. The same was true in Europe, where 83 percent of those interviewed in West Germany and the United Kingdom opposed increased reliance on nuclear power; 70 percent or more had such sentiments in Canada, Yugoslavia, and Italy. In France, where the government is heavily committed to further expansion of nuclear power, slightly more than half the public was opposed by late 1986.³⁶

This time even the experts were given pause, as was perhaps best expressed in a front-page article in the *New York Times* in October 1986:

The Chernobyl nuclear disaster is leading to major reappraisals of reactor safety and emergency planning around the world, even for nuclear plants far different from the ruined Soviet unit, nuclear experts say.

Despite statements soon after the April 26 accident that it involved a reactor design different from Western units, experts are now concluding that Chernobyl in fact has important lessons for all nuclear plants. . . .

It has long been agreed that nearly all reactors have the theoretical potential, albeit a very low one, for a disaster on the scale of Chernobyl. Now that this potential has been realized in one case, the experts now have more solid ground for worry that such an event could be repeated.

"This is the first time there has been a nuclear accident of the severity we have all feared," said Dr. Richard Wilson, a Harvard physicist who last year led an American Physical Society study on severe reactor accidents. "No one concerned with nuclear power, in the United States or elsewhere, can pretend that the Chernobyl accident makes no difference."³⁷

36. A summary of European polls for 1986 and part of 1987 can be found in Christopher Flavin, *Reassessing Nuclear Power: The Fallout from Chernobyl* (Washington: Worldwatch Institute, 1987). See also "Europe After Chernobyl: Cooler Attitudes toward Nuclear Power," *New York Times*, April 27, 1987, sec. A, p. 9; *Christian Science Monitor*, "Nuclear Power Fuels Debate in Italy," April 27, 1988, p. 7; *Los Angeles Times*, "A Year after Chernobyl, Impact Ebbs in W. Europe," April 30, 1987, p. 1.

37. Stuart Diamond, "Chernobyl Causing Big Revisions in Global Nuclear Power Policies," *New York Times*, October 27, 1986, p. 1.

The scale-up and shift in safety strategy contributed heavily to the public rejection of the nuclear power industry. Had the scale-up not occurred and regulators not changed the basic safety strategy, the eventual fate of nuclear power might have been very different.

The scale-up was not inevitable. Regulators could have insisted that reactors be kept small enough and sited remotely enough to preserve the basic safety strategy of relying on containment and distance from population centers as the last line of defense. They could also have required that experiments be performed to determine whether such reactors could really be expected to withstand the maximum credible accident.³⁸ If the results of such experiments proved ambiguous, the regulators could require stronger containment vessels.

Would such changes have prevented the antinuclear movement from arising? Certainly not, but they would have altered significantly the nature of the political debates. Sticking with small and remotely sited reactors would have constrained the almost limitless range of possible "What ifs?" to questions about the strength of containment and the magnitude of the maximum credible accident. There would still have been debates and hearings and controversy about these subjects, but the grounds for debate would have been relatively fixed, and over time it would probably have been possible to narrow the uncertainties about such questions to the point where the "What ifs?" were muted.

38. Before the shift in safety strategy the AEC had planned precisely such experiments. In 1961 it decided to build an experimental facility that could test the effects of the maximum credible accident. The facility comprised a reactor (more precisely a reactor core) about one-sixth the size of reactors then being built. The core would be placed in a containment building and allowed to melt, and the consequences then observed. The experiment would be repeated for several cores. The project was described by the Director of Reactor Development to the Joint Committee on Atomic Energy: "We will build a 50 megawatt reactor to do this. It is a small reactor as reactors go, but we will let it run up to equilibrium, so that there are plenty of fission products there, so that when they are released, we get a decent measurement of the fissions product release. And also there are other things. How much energy is released? We have to calculate the equivalent tons of TNT. We do not really know the amount of energy released in a maximum credible accident. We do not know how much the metal water reaction contributes to this. We know from experiments, small experiments what you might expect. But when you put the whole batch together, you just do not know. And the only way you will ever find out is to run [the maximum credible accident]. That is the purpose of this." U.S. Congress, Joint Committee on Atomic Energy, *Hearings on AEC Authorizing Legislation for Fiscal Year 1964*, 88th Cong., 1st sess., 1963, p. 92.

Would keeping reactors small have eliminated public fears about nuclear power? Probably not, but to the extent that small size and remote siting limited the magnitude of the potential catastrophe and made much more remote the perceived prospect of a significant release of radioactivity, smallness would have greatly dampened such fears. Would such policies have prevented Three Mile Island? It is difficult to say. But if an accident like that at Three Mile Island had occurred in a smaller reactor on a more remote site, it would not have had nearly as great an impact on public perceptions.

Altogether, the scale-up and shift in strategy stand out as the central element in the demise of the nuclear power industry in the United States. Because the scaled up American reactors were later sold to many nations in Europe and elsewhere and imitated by others, the scale-up helped lead to the nuclear industry's worldwide travails.

CHAPTER SIX

Paths Not Taken

The scale-up and shift in safety strategy represented a critical juncture in the history of nuclear power (see chapter 5). Were there other decision points which, if approached differently, might also have altered the eventual outcome and led to a more acceptable form of the technology?

By the time of the scale-up, the primary elements of the American nuclear enterprise were already in place. Through decades of controversy, public debate, endless regulatory changes, radical shifts in public opinion and economic prospects, and repeated calls for reform, the basic nuclear enterprise has remained essentially the same. Its primary characteristics emerged by the mid-1960s and despite all that has occurred since then are unchanged: light water reactors; engineered safety; and an industry of private vendors serving traditional, privately owned utilities. Could the decisions that led to light water reactors, engineered safety, and competitive private enterprise have been formulated differently enough to have evolved a more flexible and acceptable form of nuclear power? In this chapter we attempt a thought experiment.

A Different Reactor?

It is not much of an exaggeration to assert that light water reactors emerged as the dominant reactor type because of historical accident.

Light water reactors gained an insurmountable head start in the reactor development race as a result of the nuclear navy program. Yet there was nothing inevitable about the nuclear navy, or about the choice of a pressurized water reactor for the first nuclear submarine. There was considerable skepticism about nuclear submarines early on, and their emergence was due primarily (according to many observers) to the persistence, energy, and vision of one man—Hyman Rickover—and in particular to his “highly personalized approach to technological innovation.”¹

Had another person been in charge of the program, with a different vision of how technology ought to be developed, a different reactor type might well have been selected for the first submarine. If this had happened, the industrial experience with light water reactors would not have been gained, at least not until much later, and the Shippingport reactor would not have been built. Light water reactors would not have received their head start, without which they might not have participated in the competition of the 1950s, let alone won it. After all, the AEC’s Reactor Development Division originally considered light water reactors a clearly inferior choice for civilian power generation, with unexciting long-term prospects.

Thus it is not difficult to imagine a set of circumstances in which one of the other contenders won—perhaps a heavy water reactor or a sodium-cooled reactor. But would this have made a significant difference in the eventual fate of nuclear power in this country? No doubt there would have been differences in the timing of the nuclear enterprise and in the performance and economics of reactors. But as long as the overall approach was to select an economical reactor and then design add-on safety, the underlying safety problems would have remained.

The real question therefore is not whether there could have emerged a different reactor, but whether there could have been one that appreciably altered the perceived and actual safety of nuclear power. Given the historical context in which the technology was developed, such a reactor could have emerged only by accident. Reactor selection and development were governed in the 1940s and early 1950s by perceptions and motivations shaped by the immediate pressures of the era; in the following decade decisions were made on the

1. Richard G. Hewlett and Francis Duncan, *Nuclear Navy, 1946–1962* (Chicago: University of Chicago Press, 1974), p. 39.

basis of near-term economic considerations. If a significantly safer reactor had been developed under these circumstances, it could only have been as an unintended by-product of the pursuit of these other objectives.

Of course, if decision makers had known then what we know now about the public's concerns and the practical difficulties in regulating reactor safety, they might have employed very different criteria for selecting reactors for development. For example, what if the decision criteria had been turned on their head? Instead of seeking an economical reactor and trying to engineer it into a safe one, what if decision makers had sought a safe reactor and then tried to engineer it into an economical one? This approach, which we explore in some depth below, might have made a great difference.

The weakness of a safety-first approach is that without a primary emphasis on economics, nuclear power might never have come close to being economically competitive with fossil fuels. But in this respect the economics-first approach did not succeed either. It left us with an economically unviable and politically unacceptable source of energy. And safety factors were precisely the reason for its failure. Add-on safety, which contributed so heavily to nuclear power's political difficulties, led to a regulatory nightmare and endless design changes, retrofits, and construction delays, which in turn contributed heavily to nuclear power's economic difficulties. Therefore, it is not at all obvious that a concern for economics is sufficient reason to reject a safety-first approach to reactor design in favor of an economics-first approach.

Inherent Safety?

This leads directly to the second major element of the nuclear enterprise, the basic approach to reactor safety. Suppose that reactor developers really had pursued safety as the primary objective, with economics as the add-on. Might it have been possible to produce "safe" nuclear reactors—reactors that by their very nature were free from the risk of serious accidents? In light of the critical role that concerns about safety have played in the demise of American nuclear power, the notion of an inherently safe reactor is very appealing. But would such a reactor have been technically feasible?

The answer appears to be yes. As early as 1956, General Atomic

set out to build a reactor that was “so safe that it could be given to a bunch of high school children to play with, without any fear that they would get hurt.”² As envisioned by Edward Teller, the reactor would have “inherent safety,” or safety “guaranteed by the laws of nature and not merely by the details of its engineering . . . [If] all its control rods [were] instantaneously removed, it would settle down to a steady level of operation without melting any of its fuel.”³ The reactor, known as TRIGA (Training/Research/Isotopes/General Atomic), was successfully developed. More than sixty TRIGA reactors were sold, primarily to hospitals and universities that needed low-power reactors for research, producing isotopes, and training students.

Unfortunately, TRIGA was not suitable for larger reactors that could produce electricity, and so in a way was a dead end. But TRIGA was not the only effort at inherent safety. In the late 1950s General Electric explored a horizontal boiling water reactor that could have been shut down by gravity without relying on control rods. Its designers maintained that after shutdown the reactor’s decay heat could be removed by air cooling without relying on complex emergency coolant systems.⁴

Interest in such new ideas ebbed during the 1960s and 1970s, when light water reactors were ascendant. But interest in inherently safe reactor concepts revived shortly after Three Mile Island, when a small minority of nuclear engineers began to promote their development. In 1980 a Workshop on Acceptable Nuclear Futures, attended mainly by scientists and engineers who had helped launch civilian nuclear power, produced a recommendation for sustained exploration of new types of reactors that would be “inherently more forgiving” than current light water reactors.⁵ Alvin Weinberg, one of the founders of contemporary light water technology and a former director of Oak Ridge National Lab, argued:

We are convinced that existing, post-TMI reactors pose low risks

2. Freeman Dyson, *Disturbing the Universe* (New York: Harper and Row, 1979), p. 97.

3. Ibid.

4. Samuel Untermyer, *Large Natural Circulation Reactors*, General Electric Atomic Power Equipment Department report GEAP-32, class 2 (San Jose, 1959).

5. Morris W. Firebaugh and Mohran J. Ohanian, eds., “An Acceptable Future Energy System,” Condensed Workshop Proceedings, Institute for Energy Analysis, Oak Ridge, ORAU/IEA-80-3-(P), 1980.

to the public. We believe, too, that evolutionary changes to light water reactors could make them safer still. However, . . . (such changes) have tended to improve safety at the expense of greater complexity and cost. We believe that a reactor that derives safety from simple features that are inherent in the system could profoundly increase the acceptability of nuclear energy.⁶

One such reactor that has received a fair amount of attention in the years since Three Mile Island is the modular gas-cooled reactor, or pebble bed reactor. As proposed by General Atomic, each such reactor would be capable of generating less than 100 megawatts of electricity, approximately one-tenth as much as current commercial reactors. Depending on the use, such small reactors could be used either alone or linked together as modules of a larger facility.⁷ The key to the safety of this reactor lies in the combination of the relatively small size of the individual modules and the unusual nature of their fuel. The fuel is in the form of small "pebbles" each about the size of a billiard ball. Each pebble comprises a tiny kernel of uranium surrounded by a combination of graphite, carbon, and ceramic. These function like tiny containment vessels for each bit of fuel, because the component materials can withstand very high temperatures. By contrast, fuel assemblies for light water reactors employ metal rods that melt in a matter of minutes if cooling water is lost.⁸

This distinction is noted by Lawrence Lidsky, a professor of nuclear engineering at the Massachusetts Institute of Technology: "The worst possible accident for a reactor is the withdrawal of all control rods with the simultaneous total loss of coolant. A reactor can be classified level 1 (i.e., inherently safe) only if the natural processes of heat conduction and radiation are sufficient, in this worst possible case, to hold the temperature of the hottest point in the reactor to less than the fuel failure temperature."⁹ The modular gas-cooled reactor

6. Alvin M. Weinberg et al., "The Second Nuclear Era," Institute for Energy Analysis, Oak Ridge, Tenn., draft report ORAU/IEA-84-(M) (1984), p. xvii.

7. For further details see Herbert Reutler and Gunter H. Lohnert, "The Modular High-Temperature Gas Reactor," *Nuclear Technology* 62 (July 1983): 22-30; Alvin M. Weinberg et al., *The Second Nuclear Era: A New Start for Nuclear Power* (New York: Praeger, 1985), pp. 314-368.

8. Lawrence M. Lidsky, "Safe Nuclear Power," *New Republic*, December 28, 1987, pp. 20-23; "A Safe Atomic Plant for the Future?" *Washington Post*, January 10, 1988, sec. C, p. 3.

9. Lidsky, "A Safe Atomic Plant for the Future?"

and its fuel pebbles are designed to achieve precisely this objective. A small version of such a reactor has been operating in Germany since 1966; it has been subjected to a variety of deliberately induced accidents, which appear to have verified its fail-safe nature.¹⁰

Another approach to inherent safety has been suggested by the Swedish Atomic Energy Agency. It has designed a light water reactor intended to have foolproof protection not only against failures of human operators and reactor equipment, but also against such external events as earthquakes and sabotage. The protection does not require any active, engineered safety systems or human interventions, and the initial protection against meltdowns is to be sufficient for at least a week, to allow ample time for further corrective action. Moreover, the plant is designed to be still usable after any accident.

How would this reactor work? The PIUS (Process Inherent Ultimate Safety) reactor consists of a large reactor vessel of prestressed concrete, which is nearly filled with borated water (boron is a material that absorbs neutrons, thus slowing the rate of fission in a reactor). The entire core and primary coolant circuit of a pressurized water reactor are submerged in this containment vessel. In the event of any pump failure that would deprive the core of coolant, there would be no need for esoteric emergency cooling systems. Instead, natural thermal convection would draw cold water into the core from the containment vessel, which would then serve as a coolant.¹¹ The process is described by Weinberg and his associates: "No instrumentation and control equipment, valves, or pumps must operate to cope with an emergency . . . The capacity of the containment vessel is sufficient to provide cooling water for a week after such an accident before the level of the water would drop to the point where the core would be uncovered. Water could then be added to the pool from fire trucks."¹²

PIUS and the modular gas reactor are by no means the only ideas for inherent safety. General Electric has designed a reactor suspended in a pool of sodium that would cool the reactor in emergencies in a

10. Ibid.

11. For further details on the PIUS reactor see Weinberg et al., *The Second Nuclear Era*, pp. 256–313; K. Hannerz, *Towards Intrinsically Safe Light Water Reactors*, Oak Ridge, Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, Tennessee, report ORAU/IEA-83-2(M)-Rev. (1983).

12. Weinberg et al., *The Second Nuclear Era*, p. 42.

fashion similar to PIUS. Westinghouse has conducted feasibility studies of a deep-well reactor that would be constructed 2,100 feet below the earth's surface and passively cooled, thus combining core melt prevention with a novel type of containment.¹³

The notion of inherent safety seems plausible enough to merit serious examination. This leads us back to the early days of reactor development, when decision makers chose instead the path of engineered safety. Why did they opt for this approach, and what would it have taken for them to pursue inherent safety instead?

The mid- to late 1940s were a period in the history of reactor development that greatly influenced the course of American nuclear power. Decision makers were not thinking about the nature of the relationship between nuclear technology and the public; they were pioneers, exploring a young technology amid great uncertainties and doubts. Those working on the breeders doubted that there was enough uranium in the world to sustain an industry, and those working on the submarine were struggling against a growing "red menace." This was a time of concern about basic feasibility and near-term technical obstacles. It never occurred to these early decision makers that the choices they were making would go a long way in determining the shape of nuclear power throughout the world a generation or more in the future.

A decade later, however, decision makers knew they were shaping a technology that could achieve widespread use in society. Reactor developers were clearly concerned about safety by this time. As part of the deliberations over the Price-Anderson Act, Brookhaven National Lab performed a worst-case analysis indicating that if containment did fail in a core melt, the consequences would indeed be catastrophic.¹⁴ At that time the last line of defense against this potential catastrophe was a containment shield designed to withstand the maximum credible accident. Might there have been any circumstances at this point in which decision makers would have rethought their safety strategy, and seriously pursued inherent safety?

We suspect that one consideration could have made a big differ-

13. For a description of such kinds of reactors see *ibid.*, esp. pp. 26–49; Lidsky, "A Safe Atomic Plant for the Future?"

14. U.S. Atomic Energy Commission, "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants," WASH-740 (Washington, 1957).

ence: the questioning of assumptions about the maximum size of reactors. In the mid-1950s nuclear engineers and decision makers were envisioning future reactors in the range of 100 to 300 megawatts. During deliberations over Price-Anderson, for example, calculations of the worst possible damage from an accident were based on reactors of 100 megawatts or less.¹⁵ And it was believed at the time that containment shields would withstand the maximum credible effects of an accident in a reactor of that size.

We now know of course that utilities were soon purchasing reactors as much as ten times larger than this. Had decision makers foreseen this escalation in size, they might very well have rethought their basic approach to safety. They would have realized that containment could not be relied on as a last line of defense, and this recognition could have triggered serious debate about the wisdom of engineered safety.

An Alternative to Private Enterprise?

The third major characteristic of the American nuclear enterprise is that it is based on competitive private enterprise: on a privately owned supplier industry selling reactors to local and regional utilities. When the decision to have privately owned nuclear power plants was being made in the mid-1950s, two more or less separate issues became intertwined in the debate. In part, the debate was about the good and evil of public ownership, about whether atomic power had become an "island of socialism" and "another TVA." The second side of the debate was about how aggressive the government should be in promoting nuclear power; those in favor of a more aggressive role supported the public power position, as embodied in the Gore-Holifield Bill. In the end the private power advocates of course won. But it is interesting to speculate on what might have happened had the debate over public versus private power turned out differently.

There has been fairly extensive experience with publicly owned power in the United States and abroad. For example, the Tennessee Valley Authority is a large, federally owned utility: it buys plants from

15. The discussion occurs in U.S. Congress, Joint Committee on Atomic Energy, *Hearings on Government Indemnity for Private Licensees and AEC Contractors against Reactor Hazards*, 84th Cong., 2d sess., 1956, pp. 52–54ff. See also Atomic Energy Commission, "Theoretical Possibilities."

vendors, generates electricity, and then sells electricity to consumers very much the way any privately owned utility does. Electricité de France (EDF), a nationalized monopoly, is France's sole electrical utility; all its reactors are manufactured by a single firm, Framatome, and EDF supplies its own architect-engineering services, thus helping to standardize reactor design and construction. Most other nations have some measure of public ownership, monopoly, or both in the planning, ownership, and manufacture of nuclear power plants.¹⁶

Public ownership of nuclear power in the United States, however, would presumably have had to fit American legal frameworks and expectations. If the public power advocates had won in 1954–57, we conjecture that the federal government might have become the sole or primary owner of nuclear plants, taking bids from vendors, architect-engineering firms, and other private firms, in a competitive nuclear plant supply industry similar to the defense industry. A public nuclear power authority might then have sold the power generated in its plants to existing privately owned utilities, which would in turn have served their consumers. There could have been any number of variations on how to structure such an arrangement. The plants themselves could have been operated under contract by industry or by private utilities.¹⁷ Perhaps more interesting, they could have been operated by a cadre of skilled government employees akin to air traffic controllers or by the nuclear navy. Whatever the variations, the important point is that the system that resulted would look significantly different in one critical respect from the one we now have: instead of about four dozen utilities independently owning and making decisions about nuclear power plants, there would be just one.

Would this have made any difference in the fate of nuclear power? Possibly the clearest and most important point at which it could have was in the mid-1960s, at the time of the rapid scale-up. It is intriguing

16. On France see Dominique Saumon and Louis Puiseux, "Actors and Decisions in French Energy Policy," in Leon Lindberg, ed., *The Energy Syndrome* (Lexington, Mass.: Lexington Books, 1977), pp. 119–172; Dorothy Nelkin and Michael Pollak, *The Atom Besieged: Extraparliamentary Dissent in France and Germany* (Cambridge: MIT Press, 1981). On Britain see David Collingridge, *Technology in the Policy Process: Controlling Nuclear Power* (London: Frances Pinter, 1983). A good comparative assessment is in John L. Campbell, *Collapse of an Industry: Nuclear Power and the Contradictions of U.S. Policy* (Ithaca: Cornell University Press, 1988), pp. 136–180. See also the sources cited in n. 43, chap. 1.

17. On the many possible arrangements for government in collaboration with private industry see E. S. Savas, *Privatization* (Chatham, N.J.: Chatham House, 1987).

to consider whether a single customer rather than many independent ones would have ordered so many reactors so quickly. And would a single, government-owned public nuclear authority have sought to purchase larger and larger reactors, without waiting to see how the last ones it ordered were going to perform? Even if its policy makers wanted to, would Congress really have granted them the authority or funds to purchase a hundred reactors at about \$140 million to \$300 million each in the late 1960s?

Public ownership could have made a difference in another respect: there is excellent reason to expect that it could have prevented the American nuclear industry from becoming the only major one in the world to have virtually every power plant practically custom-built. The reasons for this lack of standardization can be traced largely to the industry's competitive characteristics:

1. Two basic reactor concepts instead of France's one: General Electric adopted the boiling water reactor partly because it looked less expensive and partly to differentiate GE's product from the pressurized water reactor sold by Westinghouse, its major competitor;
2. Four manufacturers (originally five), each with different designs;
3. Multiple sizes and periodically updated designs from each manufacturer, partly to make sales with the latest technology and partly to appeal to the diverse needs of the several hundred potential utility customers;
4. Twelve architect-engineering firms competing for the utilities' design and construction business on the nonnuclear portions of the generating plant by custom-tailoring their bids.

It is easy to see why so many separate, competing firms would have had a much harder time standardizing than did the one manufacturer and one national utility in France. In addition to the incentives for making one's product distinctive in a competitive sales environment, antitrust laws also helped stifle the collaboration that would have been necessary to bring about standardization. Altogether, though manufacturers began to move toward standardization as early as the mid-1960s and the Atomic Energy Commission actively

promoted it after 1972, standardization was never achieved.¹⁸ By the time a serious effort got under way in the mid-1970s, it was a case of too little, too late.

A single customer would also have enjoyed superior opportunities to learn. In total, the United States has built more reactors than any other nation, but each customer has gained only limited experience because it has ordered and operated only a few. As a result, most customers have not been very knowledgeable and have been unable to impose standards of quality on suppliers. Markets are normally more efficient than governments at holding costs down and quality up, but only if customers know what they are buying. In this case, a single public customer would have been in a position to learn from every reactor order. Although perhaps naive at the outset, the government organization would have acquired sufficient experience to become knowledgeable and demanding. This could very likely have imposed on the reactor supply industry a discipline that for too long in the United States came only from the regulators if at all.

For the same reasons, a single customer could have acquired more knowledge and sophistication about the operation of reactors. Many utilities started their nuclear operations without adequately expert staff, and more than a few never acquired the necessary expertise and training. Some observers have argued that reactor operators ought like air traffic controllers to be viewed as a specialized cadre and required to undergo a rigorous, centralized training program. Such an arrangement could have been a natural outgrowth of having a single customer. So too could have been nuclear reservations—clusters of reactors situated in remote sites. Thus although most of Canada has favored hydropower and fossil fuels rather than nuclear power, the utility serving the province of Ontario owns twenty reactors and is considering four more; eight reactors are at each site. Such an approach would have been much more compatible with a single, national customer than with the decentralized approach we inherited.

There is obviously no way of knowing for sure whether these potential benefits would actually have been realized. It is possible

18. See David L. Bodde, *Regulation and Technical Evolution: A Study of the Nuclear Steam Supply System and Commercial Jet Engine* (Ph.D. diss., Harvard University, 1976). For a brief institutional analysis see Campbell, *Collapse of an Industry*, pp. 31–49.

that the government would simply have contracted with individual utilities to have plants built and operated, in which case the results might have been very similar to the ones we got. Or the single public owner might have mismanaged the construction and operation of reactors at least as much as some utility companies did—NASA's stewardship of the space shuttle program offers all too vivid a comparison.¹⁹ And even if the public power scenario had worked more or less as outlined, it might still have been insufficient to change the eventual outcome. What is clear, however, is that a change in ownership could have made a big difference. We believe the ownership issue becomes especially relevant in contemplating a revised approach to nuclear power (see chapter 8).

The obvious objection to replacing the private system of utilities with a single, public owner is that the system would be less subject to market forces and might therefore produce power less economically, thus jeopardizing the low cost that nuclear power must have to compete with fossil fuel. But this objection is easily overcome. Market discipline would still be imposed as long as a single owner had to sell electricity to the private utilities. Utilities would agree to buy the electricity only if they found it cheaper or less risky than expanding their own fossil fuel capacity. Supply and demand projections would still be based on the individual utilities' views of future trends, and the price to consumers would still be based on the marginal costs of alternatives available to the utilities.

A more subtle argument against a single, public owner is that the government would be encouraged to subsidize inefficient power. Imagine that the single owner had ordered ten plants in the mid-1960s, based on utility projections of supply, demand, and relative cost, and that by the early 1970s it had become clear that the costs of nuclear power would be significantly greater than anticipated, and that power produced by government-owned plants would not be competitive with power produced by coal. Given its investment in the construction of the plants, the government might decide at that point to subsidize the price of electricity generated by nuclear plants, to have it compete with coal. It might be argued that such a subsidy would be economically inefficient.

This may be true. But it is not at all obvious that the resulting

19. John Logsdon, "The Space Shuttle Program: A Policy Failure?" *Science* 232 (1986): 1099–1105.

costs would be any greater than those now incurred by decentralized owners. Because plant orders would be based in each case on utility projections of demand and price, the inefficiencies resulting from higher costs of nuclear power than expected might be roughly comparable. In fact, because fewer plants would probably have been purchased by a single owner, the overall inefficiencies might be smaller, and the burden would be distributed broadly, among all taxpayers, rather than concentrated locally among the investors and customers of local utilities with especially bad experiences, like the Washington Public Power Supply System.

An argument could even be made that such a subsidy for nuclear power, although inefficient in a narrow economic sense, might be efficient from a broader, societal perspective. Nuclear power plants do bring public good with them: a diversified base for energy security and a reduced dependence on coal, especially important in a period of growing concern about the greenhouse effect and acid rain. Or, to state it more formally, the price of electricity generated using fossil fuels fails to reflect the entire price that society will eventually pay in coping with the externalities. A local economic inefficiency is therefore not sufficient argument against a subsidy for nuclear power, and the potential for such a subsidy is not a compelling reason for rejecting government ownership of nuclear plants.

Looking back at the three primary characteristics of the nuclear industry, we conclude that each could have developed differently: alternatives were available to light water reactors, engineered safety, and private power. Some of these would have directly affected the approach to safety taken by the nuclear industry and thus eased public concerns about safety, the issue that underlies most of the problems that afflict nuclear power.

Of the three main elements, the one that is easiest to imagine having turned out differently is the dominant reactor type. In only slightly altered historical circumstances, another reactor design might well have emerged. But although this would have been the easiest element to change, it would also have made the least difference. Much more important were the criteria governing selection and development of reactors. Had decision makers emphasized safety first and then economics rather than the other way around, the fate of nuclear power might have been very different. An emphasis on safety first would

have led to a serious examination of inherent safety, which in turn could have altered the regulatory system, public reactions, and perhaps even the ultimate economic appeal of nuclear power.

The case is less clear with respect to private ownership of nuclear power. Had the advocates of public power succeeded, the system would have evolved into a much more centralized system than we now know, and this could have greatly altered the market interactions between vendors and buyers. A single, more knowledgeable customer might have driven the system in a very different direction, one potentially more compatible with public acceptance. Whether the changes would have been great enough is difficult to judge.

CHAPTER SEVEN

Democratic Control of Technology

This inquiry began with a simple question: How and why did the American political system produce a form of nuclear power unacceptable to the public, and what can we learn from the experience about fundamental problems in the relationship between technology and democracy? The unhappy outcome is not a tragedy, for actual damage to life and property has been remarkably low. An affluent nation can afford to invest in technology that does not succeed, and our political system is robust enough to cope with considerable conflict. Still, no one would deliberately create such a bitter, costly, and sometimes frightening experience if it could be avoided. To do better in the future, it makes sense to figure out what lessons the demise of American nuclear power offers for helping to understand technology as a political phenomenon.

Our primary focus will be on the relationship between technology and democracy, which we see as the core of the nuclear power experience. Although nuclear advocates may not really believe their preferred technology to have been ruined by an ignorant public, sometimes they sound as if they do. Likewise, nuclear opponents have spoken as if nuclear technology rode rampant over democratic values. An intelligent society would want to protect against both eventualities: democracy taking technology in senseless directions, and technology taking society in unacceptable ones. If a society wanted to

combine more intelligent guidance of technology with enhanced popular control, what insights does the nuclear power experience offer?

Who or What Controlled Nuclear Technology?

One of the specters raised in chapter 1 was the possibility that technology is coming to dominate human affairs so much that we rush to implement new technologies whenever the opportunity arises, regardless of society's needs and goals. It must be admitted that civilian nuclear power had an element of this at its inception. The technology clearly was not launched as part of a conscious search for new energy alternatives especially suited for replacing oil or coal. In this sense, a technological opportunity drove society, rather than the other way around. Scientists and engineers, decision makers in the navy, and members of Congress became enamored with a new technology and set out to see what could be made of it.

But what policy makers chose to do with nuclear power was very much in keeping with the goals they already held: faster submarines that could stay submerged longer and counter the "red menace," enhanced international prestige for the United States, inexpensive electricity using large, centralized sources. Therefore, the technological opportunity offered by nuclear power did not induce decision makers to do things to which they were not already amenable. Looked at from this perspective, the nuclear case provides support for the arguments of the technological rationalists: nuclear technology provided a new means to existing ends.

Nor did policy makers get caught up in a process where they were outmaneuvered by technical experts because events moved too fast, or considerations became too esoteric for ordinary judgments, or technology otherwise appeared to be running the humans instead of vice versa. Light water reactors were given their initial boost by the nuclear navy, whereas they were considered mundane by the experts in the Atomic Energy Commission's Reactor Development Division. Both Democrats and Republicans on the Joint Committee on Atomic Energy pushed for more rapid exploitation of civilian nuclear energy, urging forward both the AEC and private industry. In conjunction with high-level management at the electric utilities, executives in the nuclear industry made the fatal missteps of scaling up. Altogether, non-technical decision makers made the critical decisions that shaped this

technology, except perhaps for the choice of complex engineered safety systems. And they did so on the same basis as for other, less esoteric technologies: get long-desired results by using newly available means.

What about the possibility that the technology was effectively out of society's control because decisions were made by a nonrepresentative group of elites? There is little question that the original decisions were made by a relatively small group without the widespread consultation and debate that often accompanies major decisions.¹ Congress disbanded the Atomic Energy Commission and the Joint Committee on Atomic Energy in 1974 precisely because they were perceived to be biased toward the nuclear industry and not fully representative of congressional opinion. But were these organizations really unrepresentative of public views in the 1950s and 1960s? We think not. A poll conducted in 1956, for example, found that 69 percent of those interviewed expressed "no fear" about having a nuclear power plant in their community.² More generally, a broad consensus favored nuclear power until the 1970s, and majority support continued until after Three Mile Island.³ Indeed, the low level of participation in the debate in the early years reflected the high degree of consensus on the issue: very few outsiders criticized what was going on because there were few opponents. It was only when such groups did emerge in the late 1960s and early 1970s that the process began to seem biased and unrepresentative.

What about congressional decisions of the mid-1950s favoring private enterprise? This was the most strongly contested issue in the early political history of nuclear power. Private and public power advocates throughout the political system had many opportunities to make their case, and Congress repeatedly reaffirmed an intention to have private industry commercialize civilian nuclear power. The choice turned out to have unfortunate consequences, but it was about as deliberate a choice as humans ever make on such matters. This is not to say that the ideological congressional debate foresaw and faced

1. On this period see James R. Temples, "The Politics of Nuclear Power: A Subgovernment in Transition," *Political Science Quarterly* 95 (1980): 239-260.

2. Hazel Gaudet Erskine, "The Polls: Atomic Weapons and Nuclear Energy," *Public Opinion Quarterly* 27 (1963): 155-190, esp. pp. 189-190.

3. William R. Freudenberg and Eugene A. Rosa, eds., *Public Reactions to Nuclear Power: Are There Critical Masses?* (Boulder: Westview, 1984).

up to all the implications of a private nuclear enterprise, only that constrained participation was probably not the fatal flaw.

As for the rapid scale-up in reactor sizes in the mid-1960s and the bandwagon market that produced nearly a hundred orders for giant reactors in just a few years, these emerged primarily from a decentralized, market process among reactor vendors and utility companies, fed in large part by a desire to achieve economies of scale. In this sense, the nuclear power experience conforms to the views of those who criticize the "privileged position" of business, for business executives made the key decisions without having to be publicly accountable.⁴ But the tack pursued by business was widely applauded: the rapid scale-up in reactor orders and sizes was perceived in its time as a triumph of American ingenuity and private enterprise. The great bandwagon market was exactly what Congress had been pursuing for more than ten years. And when the AEC and the joint committee were informed that containment had become unreliable for large reactors, and that emphasis from that time would have to be placed on preventing all accidents, they supported the change and did not even seriously debate limiting the size of nuclear plants. Nor was there a suggestion from any outside scientists or interest groups that this should be considered.

It would be tempting to attribute this to ignorance about the change that would be required in safety strategies. Not until 1966 did the Advisory Committee on Reactor Safeguards (ACRS) first discuss the China Syndrome. But even when technical experts belatedly recognized that a core melt could breach containment, they did not suggest canceling or slowing the scale-up. One member of the ACRS did say that there should be a limit on the maximum size of reactors, but he drew the line at reactors the size of that at Browns Ferry (about 1,000 megawatts). That was beyond the size at which containment could be breached by a full meltdown, so adopting his suggestion would not have made an appreciable difference.⁵

Had there been an active antinuclear movement at the time, there is a reasonable chance that the issue would have become a focus for debate. But there was none; nuclear policy makers were still operating

4. Charles E. Lindblom, *Politics and Markets: The World's Political-Economic Systems* (New York: Basic Books, 1977).

5. David Okrent, *Nuclear Reactor Safety: On the History of the Regulatory Process* (Madison: University of Wisconsin Press, 1981), pp. 103–132, 137.

in an environment of remarkable consensus and technological optimism. From the public's perspective there was no reason for dissent or opposition to the process. It was all working out just fine. In ten short years, Congress, the AEC, utilities, and vendors had taken an immature, small-scale technology and turned it into a dramatic new source of energy.

One of the striking features of the nuclear power story is the extent to which technology did not dominate human will. Except for the earliest years, technical experts were not really in charge of framing the enterprise; the key decisions were sociopolitical more than technical. The first lessons of the nuclear experience is that the system worked: we got pretty much what was sought by legitimate elected representatives, duly appointed civilian and military bureaucrats, and executives of businesses that government lured into working on the technology. In this sense, the nuclear power experience is something of a vindication for democratic processes.

A Rotten Outcome: Why?

Although the story of nuclear power is one of technology being steered by broad political choices, even the most ardent democrat would have to concede that political and economic choices helped lead to distortion and eventual abandonment of a potentially promising energy technology, during a period when fossil fuels looked increasingly dubious as a long-term source of energy. If this was a victory for democracy, it was a pyrrhic one.

In the long run, the navy has proven to be the only clear winner. Some utilities have operated plants at a profit, but for most electric companies nuclear power has been more trouble than it is worth. A number of nuclear scientists have had satisfying careers in spite of the controversy surrounding their enterprise, but many have been deeply wounded. Some elected officials and bureaucrats may have cared more about their short-term successes than about the long-term debacle of nuclear power; most, however, never profited from the controversy. And in spite of successful imposition of the public will, millions of people still live near reactors they perceive as threatening. Even if no further nuclear facilities are constructed, some existing ones may not be decommissioned and decontaminated for as long as half a century. The industry's failure has also exacted a high price,

and further rate increases will be borne by consumers of electricity to pay for power plants now going into operation or being canceled. For the great majority of us the outcome has been unfavorable, and in that sense the system did not work. As Langdon Winner puts it, "While someone, somewhere is making decisions and choices, things are also running amok."⁶

Is this the normal condition of democratic control of technology? If not, what threw off the usual process by which technology is steered in ways that end up being generally acceptable to the public? Compare nuclear power with other major programs that have endured over several decades. How many have had so much invested for so long, and then ended up being widely perceived as unacceptable? Only the Vietnam War seems comparable. Most "big government" programs since Roosevelt were criticized fiercely at the outset, and periodically are shown to be less efficient and effective than is desirable; but generally they either get dropped after a short time or become widely accepted.

Even other risky technologies somehow become acceptable. When recombinant DNA research first emerged in the 1970s, it seemed headed for the same fate as nuclear power. In opposing research at Harvard, the mayor of Cambridge declared, "They may come up with a disease that can't be cured—even a monster. Is this the answer to Dr. Frankenstein's dream?"⁷ Press coverage was extensive and sensational. One article bore the headline: "Science That Frightens Scientists."⁸ During 1977 sixteen proposals for regulating the technology were introduced in Congress, and more than two dozen hearings were held on the subject. Yet by 1980 the controversy had virtually disappeared.⁹

Nor is this an isolated exception. Steamboats and trains were

6. Langdon Winner, *Autonomous Technology: Technics-out-of-Control as a Theme in Political Thought* (Cambridge: MIT Press, 1977), p. 56.

7. Quoted in Clifford Grobstein, *A Double Image of the Double Helix: The Recombinant DNA Controversy* (San Francisco: W. H. Freeman, 1979), p. 66.

8. William Bennett and Joel Gurin, "Science That Frightens Scientists: The Great Debate over rDNA," *Atlantic*, February 1977, p. 43.

9. For a good review of the controversy see Sheldon Krimsky, *Genetic Alchemy: The Social History of the Recombinant DNA Controversy* (Cambridge: MIT Press, 1982). A brief overview and analysis of the strategy employed against the potential risks of rDNA are contained in Joseph G. Morone and Edward J. Woodhouse, *Averting Catastrophe: Strategies for Regulating Risky Technologies* (Berkeley: University of California Press, 1986), chap. 4.

especially dangerous in the early years. Pesticides were widely distrusted and remain so. Coal is obviously dangerous to miners, as well as to those who breathe polluted air. Chemical plants occasionally release dangerous substances, and hazardous cargo is routinely involved in road accidents. None of these technologies is fully compatible with environmental values and most have hurt more people every year than American nuclear power has in its entire history, yet each has proven acceptable enough to be continued. Not "safe" perhaps, but acceptable.

What unifies all these examples? Quite simply, when problems associated with them came to public attention, enough precautions were taken and modifications made to render the risks more acceptable. When major social and technological programs succeed, it is usually not because selfless, farsighted government or business leaders make a single wise decision. Instead, in a process that Lindblom calls the "intelligence of democracy," policy achieves acceptability gradually as it evolves through a series of adjustments. Multiple, partly conflicting sets of leaders compromise to take account of each other's views, especially those underemphasized in the original decision.¹⁰ The initial policy is revised in small, reversible steps in response to feedback about errors, interpretations, and changing perceptions of needs and opportunities. Ordinarily, representative governments and market-oriented economies are relatively receptive to criticism and likely to act on it. This is true in part because competing businesses and candidates often benefit by correcting (that is, exploiting) the excesses and errors of others, but rarely gain enough support to take radical departures from the status quo that could result in especially damaging new errors. The essence of this democratic process of correcting errors is to revise decisions gradually, thus evolving increasingly acceptable outcomes through a series of successive approximations.

To some extent, this process of serial adjustment did occur with nuclear power. The history of reactor regulation in the 1970s is one of continuous adjustment of design and operating regulations in response to perceived shortcomings. In fact, some in the nuclear industry would argue that there was so much such error correction that safety problems were made worse. Whether or not this is accurate,

10. Charles E. Lindblom, *The Intelligence of Democracy* (New York: Free Press, 1965).

nearly two decades of error correction have clearly failed to make the technology more acceptable. Even huge amounts of negative evidence did not lead to more acceptable nuclear power. The process of error correction that has gradually produced acceptable policy in so many other domains did not work in nuclear power. Why not? Why did the usual process not bring the technology into greater alignment with the public's wishes? What was it about nuclear power that made it responsive to political forces in its early days, but unresponsive in the 1970s once the public began to have doubts?

Technological Inertia

Thomas Parke Hughes describes the early evolution of the electric power system as follows: "As a technological system grows, it develops an internal dynamic which makes it difficult for external factors to change the direction of its evolution. . . . In the field of electric power, this momentum emanated from large amounts of capital investment, the growth of electrical manufacturing firms, the development of electrical engineering education and the activities of professional engineering societies."¹¹ Hughes might just as well have been speaking about the nuclear power enterprise. Once light water reactors gained their head start, they developed an almost irresistible momentum. By the mid-1960s alternative approaches were no longer seriously considered (other than breeders for the distant future). There followed two decades of regulatory changes in reactor design and operation, but virtually all such modifications were variations within an unchanging basic approach. The momentum effectively precluded serious exploration of alternative technologies and significantly different approaches to safety.

This inertia derived from two closely related factors that are inherent in a large-scale technology such as nuclear power: time lag and scale. Development of a particular type of reactor is a long-term process. Even with the acceleration that resulted from the efforts of the nuclear navy, it took some fifteen years to develop light water reactors to the point where they could be offered to utilities as practical power producers; it took roughly ten more years to build these

11. Thomas Parke Hughes, *Networks of Power* (Baltimore: Johns Hopkins University Press, 1983), p. 15.

reactors and bring them on-line, and establish the associated regulatory regime. The reactors are likely to have an operating life of about thirty years, so we can say that one complete generation of the technology lasts on the order of half a century. This time lag builds inflexibility into the system, simply because it would take so long to develop an alternative reactor to the point of practicality. When public doubts began to emerge in the mid-1970s, the light water reactor had been under serious development for a quarter-century. The prospect of having to relive that long development cycle in the pursuit of an alternative, even if the cycle could be shortened somewhat as a result of learning that had accumulated in the intervening years, was enough to daunt even the most ardent advocate of significantly different approaches to the dominant reactor technology.

This inertial effect was reinforced by the sheer scale of the development process, involving billions of dollars, thousands of careers, and a widespread complex of interrelated organizations. Development of light water reactors began as a small-scale, exploratory effort, but by the early 1950s it had become a major concern of some of the world's largest research and development facilities and a new, fast-growing government agency. By the late 1950s two of the nation's leading industrial enterprises had committed themselves to becoming suppliers of light water reactors, and their efforts drew in an increasing number of suppliers, subcontractors, and architect-engineering firms. By the early 1960s public utilities from around the country began to bet their futures on this particular approach to nuclear power. With the utilities came a regulatory infrastructure that gradually evolved over two decades of experience, all focused in painstaking detail on light water reactors. In short, once a particular reactor technology gained momentum, the monetary and organizational investment required to bring it to fruition led to a massive social and institutional complex. As with the time lag in reactor development, the prospect of having somehow to slow down this snowballing complex and start all over again with a new approach was a major impediment to seriously considering alternative reactor types.¹²

12. Inertia in reactor development is explicitly addressed in Freeman Dyson, *Infinite in All Directions* (New York: Harper and Row, 1988), chap. 8. For more extended treatment of the problem of inertia and inflexibility see the following works by David Collingridge: *The Social Control of Technology* (London: Frances Pinter, 1980) offers a general analysis of the problems of lead time, entrenchment, and other aspects of large-

Similarly, major adjustments in the safety strategy were a daunting prospect. Their ramifications would have been felt throughout this widespread enterprise—in the design of reactors already operating, in reactors under construction, in the economics of nuclear power, in the regulatory system, in the production process, in the siting process, and so on. Even within the confines of the existing reactor technology, error correction was constrained; modifications of reactors under construction consisted of complicated layers of redundancy worthy of Rube Goldberg or wider margins of error, tacked onto a basically unchanged original design. And once a reactor site was completed and operating even many of these options were foreclosed. The kinds of changes to existing reactors on existing sites that might have made a difference to public acceptability (for example, double containment shields) were so expensive that they would have dramatically altered the economic profile of the reactor. The real choices were thus highly constrained, and sometimes came down to take it or leave it. For example, by the time it became apparent that the Shoreham nuclear plant might prove politically unacceptable, more than \$4 billion had already been invested.

Technical inertia gradually created intellectual inertia. The expanding organizational complex devoted to commercializing nuclear power brought with it trade associations, professional societies, and university departments. A new profession was born—nuclear engineering. The social and intellectual infrastructure associated with this organizational complex focused naturally on large light water reactors with engineered safety. Everyone who might have been a creative, countervailing force was essentially co-opted into the system, and large light water reactors built with engineered safety were the only game in town. University departments of nuclear engineering emphasized light water reactor technology to prepare their students for jobs in the nuclear industry. At the same time, members of the faculty consulted for the firms that were building and operating the current generation of technology. Any research contracts that university researchers won from government likewise focused on the dominant approach—or on alternatives like the liquid metal fast

scale technology that cause inertia; *Technology in the Public Process: Controlling Nuclear Power* (London: Frances Pinter, 1983) deals specifically with the nuclear power problem.

breeder that were expected to replace light water reactors in the long term.

This intellectual inertia reinforced the technical inertia, so that the likelihood of changing directions grew smaller and smaller. The nuclear power enterprise after 1965 was thus almost perfectly designed to frustrate correction of anything more than minor errors. The scale and time lag of the effort to bring the light water reactor to fruition created a technological momentum that rendered virtually impossible the usual political means by which major social choices are gradually refined: if decision makers did not get the scaled up nuclear program right the first time, it would be almost impossible for them to fix it. As a result, the learning has been of about the worst sort possible. After thirty years we have learned that we do not like what we have inherited, and that we do not have any options on which to fall back. Our options are to take it or leave it. Most of society prefers to leave it, to build no more nuclear power plants unless forced to do so by a cutoff of oil, the greenhouse effect, or the like. Thus even though nuclear power was not the unstoppable and autonomous force depicted by some critics of technology, it did prove to be an unshapable force.

The Malleability of Technology

In the end, despite the strong influence that government exerted in framing the basic approach to nuclear power, despite the eventual rejection and shutoff of the technology by normal democratic processes, the polity was not able to shape nuclear power in the way that it shapes many other policy domains. The nuclear power enterprise took on a life of its own and became relatively impervious to the normal political learning process.

Does this mean that there is some inherent incompatibility between large-scale technology and democracy, that technological inertia cannot be controlled by the serial, error-correcting ways of democratic institutions? We believe the answer is yes in one respect: technological momentum is inevitable. Powerful inertia invariably sets in once a decision is made to build numerous, multibillion-dollar units of a complex new technology, and the massive institutional framework necessary to operate, maintain, and regulate the enterprise begins to emerge. This inertia will constrain the kinds of adjustments

that can be made: if dissatisfaction with the system grows deep enough, the constraints will force the kind of take-it-or-leave-it decision that our society faced with nuclear power. In this sense, the nature of large-scale technology and the nature of democratic learning do conflict.

On the other hand, the form that a technological enterprise takes does not have to be incompatible with the preferences of the public. There was nothing preordained about the exact type of technology and regulatory system that we inherited. True, the head start that light water reactors enjoyed made their dominance likely. But they did not have to be large reactors, nor did they have to rely primarily on prevention for the last line of defense. Reactors did not have to be so close to cities, nor sold in such large numbers so quickly.

In hindsight, it is not difficult to identify the point at which the system became locked in. In just three years in the mid-1960s, nuclear decision makers dramatically scaled up the size of reactors, contracted to build a large number of them, and shifted from containment to prevention as the last line of defense against catastrophic accidents. These three steps in this short period locked the United States into a particular form of nuclear technology around which the momentum developed and against which the public ultimately rebelled.

But this was not unavoidable. Regulators could have insisted that reactor sizes be increased more gradually, and that time be taken at each step to acquire operating experience before proceeding to larger sizes. They could have insisted that the new technology be diffused at a more deliberate pace. This would have allowed time for the regulatory process to become firmly established and for policy makers to assess public acceptability of the new technology—and modify the technology accordingly. Federal policy makers could have insisted on running experiments (some of which had been planned) that might shed light on the major risks associated with the technology and the major sources of public concern (such as the consequences of a serious core melt).¹³

Such a go-slow approach would of course have seemed terribly inappropriate in the mid-1960s when nuclear power was an American success story. Science, industry, and government seemed to have proven again that they could push back the frontiers of knowledge

13. See n. 38, chap. 5.

and accomplish technological miracles in the service of humanity. This was an era of global technological, economic, and political leadership for the United States, which was going to the moon, building the Great Society, stopping communism in Southeast Asia—and was apparently well on its way to an inexpensive and virtually inexhaustible source of energy. It seemed entirely reasonable for it to push ahead, scale up, bring the new technology to its own society, and export it wherever feasible. The market seemed to be demanding it, and American industry was responding.

That a more cautious approach would have seemed foreign to the times speaks precisely to the point. The rapid scale-up and diffusion, and the concomitant shift in safety philosophy, were products of political and economic decisions and judgments of the time. As a thought experiment, consider what might have happened had the same choices been faced twenty years later, in 1985, after the political culture had become more conflictual. The factors that determine public acceptability would be fairly well understood. The corps of science journalists would be far larger and more sophisticated than in the 1950s and 1960s, so that information presented by the news media would be of a somewhat higher quality. Administrative agencies would expect their decisions to be challenged in court, so that more scrupulous adherence to hearing requirements and other procedural norms could be expected; among other by-products, decision making would probably be substantially slowed down. Within industry, environmental attorneys would have far more authority, and liability concerns would occupy a much larger role in corporate decision making. And Congress would be most unlikely to allow major new endeavors without prolonged inquiry, hearings, at least one major study by the Office of Technology Assessment, and partisan arguments from numerous conflicting committees and subcommittees.

Altogether, if the relatively dispute-free deliberations of the mid-1960s about containment, remote siting, and reactor sizes had originated in the mid-1980s or later, policy makers would probably have viewed their options quite differently. Double containments, remote nuclear reservations, smaller reactors, and inherent safety would all have been given much more serious attention. And in the process, a different and more acceptable form of nuclear power might have been forged. Inertia would still develop around this somewhat different form of the technology, and nuclear power would still seem question-

able to some critics; but the overall enterprise around which the inertia developed would almost certainly have been shaped in a fashion more acceptable to a working majority of political elites and the public.

Of course, even if the technological form is shaped by extensive public debate, there is no guarantee that it will be well matched to the values of society twenty or thirty years after the debate. The inertia that governs technological development locks the technology into a form that reflects society's values at the time of the public debate, but society's values change continually, albeit usually slowly. The technological form might reflect the values of society at the time of the debate, but these values may or may not be consistent with those of future generations. We can easily imagine that thirty years from now, the dominant worry about nuclear power will not be over economics, as it was in the 1950s and 1960s, or operating safety, as it was in the 1970s and 1980s, but over vulnerability to terrorism. A public debate in the early 1990s could conceivably lead to a new reactor that is more susceptible to terrorist attacks than other types of safe reactors would be, and thus to a reactor that might have been acceptable to society at the time of the debate but unacceptable by the time it was ready for widespread use.

Inertia creates an unavoidable risk. Even with extended public debate, there is no guarantee that the technological form shaped today will prove acceptable tomorrow. But broad public debate at the outset greatly enhances the likelihood of future acceptability; for the wider the range of values taken into consideration in shaping the technology, the smaller the chances that a future concern will go untreated. Although it would not be a dominant consideration, the threat of terrorism would be raised now in a serious nuclear debate, and it could easily swing the balance in favor of one class of inherently safe reactors rather than another. There is no guarantee that some other value might not emerge thirty years hence; but the broader the debate and the longer it is carried out, the smaller that risk becomes.¹⁴

If this line of argument is plausible, then we cannot conclude that the particular form nuclear power took was the result of some underlying technological imperative: instead, it was the result of po-

14. This is where the issues of competence and democratic participation come together: there is an intelligence to democracy, as is argued by Lindblom in *The Intelligence of Democracy*.

litical and economic decisions and processes. Once the decision to proceed with the particular form on a large scale was made, considerable inertia was inevitable. But when to proceed, and with what form to proceed, was very much a matter shaped and controlled by political forces. Had the political culture been better prepared to mount a serious, pluralistic debate about nuclear power in the mid-1960s, the United States would quite possibly have produced a more acceptable form of nuclear power.

But Can Democracy Sensibly Shape Technology?

In principle, technology may indeed be subject to political control. But is democratic practice really capable of shaping technology in sensible ways? The results for nuclear power have been sufficiently unappealing that they raise serious questions about the ability of democracy in application to manage the complex societal issues created by large-scale technology.

These questions are reinforced by a widespread, almost intuitive sense that technology is a breed apart from other policy issues. It seems more complex, less accessible to the average person. We can listen to the secretary of state talk about Central American policy and feel capable of drawing our own conclusions. We can listen to a debate about abortion, highway funding, or education, basically understand the issues, and feel reasonably confident about our ability to judge them. But technology is different; it seems harder to understand and many people feel more dependent on experts.

This sense that technology is different leads both those who are enthusiastic about technology and those who are skeptical of it to conclude that democracy and technology conflict. Many proponents of technology believe that decision making in this domain is too complex to be handled by the public and democratic institutions, and must instead be entrusted to knowledgeable elites. Many who are uneasy about technology perceive large-scale technical endeavors as simply too difficult to be controlled either by the public or by elites, and believe they should be eschewed wherever feasible. According to one view, the public and democracy are not capable enough; according to the other, technology is too complex even for elites to handle. In the following pages we consider these views in turn.

Is the Public Capable Enough?

Some observers have argued that the public's evaluation of risky technologies is at base irrational. The problem lies with an apparent desire for zero risk. It is not enough for nuclear technology to be safer than the available alternatives; the public demands absolute safety, which both in practice and in principle is a chimera.¹⁵ This view is bolstered by social psychologists' studies showing that many people are poor intuitive processors of information about the probability of accidents. It is also clear that systematic biases cloud individuals' perceptions; thus familiar technologies, such as dams, are seen as less risky than unfamiliar technologies that pose no greater a threat. Technologies with frequent accidents of low consequence (like automobile travel) are viewed as less risky than technologies with a lower probability for accidents of larger consequence (like nuclear power).¹⁶

While it is true that people do not think like professional risk assessors, the overall nuclear experience on balance does not suggest an irrational public. True, at a fine level of detail, the perceptions and attitudes of most individuals are not precise or consistent. But when viewed from a distance, from the perspective of a quarter-century of experience, the overall evolution of public perceptions about nuclear power looks quite rational—given the information, evidence, and events seen by the public over that time.

Because of the complexity of the technology, few people have been in a position to judge for themselves the safety of nuclear power. But the public is often confronted with issues that it does not completely understand, either because the investment of time required to master the issue is impractically large or because the issue itself is simply too arcane (for example, arms control). People still develop opinions and political processes still function. How does the public cope with issues it does not understand? By relying on such time-tested, commonsense rules of thumb as party loyalty, ideology, or the lead of trusted public figures or editorial pages.¹⁷ If the history of public perceptions of nuclear power is viewed in this light—as a

15. See for example Aaron Wildavsky, "No Risk Is the Highest Risk of All," *American Scientist* 67 (January–February 1979): 32–37; Richard Wilson, "Analyzing the Daily Risks of Life," *Technology Review* 81 (February 1979): 41–46.

16. Baruch Fischhoff et al., *Acceptable Risk* (New York: Cambridge University Press, 1984).

17. Stanley Rothman and S. Robert Lichter, "Elite Ideology and Risk Perception in Nuclear Energy Policy," *American Political Science Review* 81 (June 1987): 383–404.

pattern of responses to the cues and signals the public was receiving—then those perceptions begin to display a rather sensible pattern.

Until the late 1960s the public's perceptions of nuclear power were positive. The reason seems straightforward: there appeared to be an overwhelming consensus in favor of the technology within the scientific community, government, and industry, at a time when trust in these institutions was high. All the signals being conveyed to the public were positive; under the circumstances, it would have been irrational to view the technology in anything other than a positive light.

But the signals changed in the 1970s. Consensus began to break down, as regulatory debate followed regulatory debate. Suddenly the public was confronted with a very different situation: the apparent experts no longer seemed to agree. Where once there had been unison, there now seemed to be bickering, controversy, and even confusion.

When the experts no longer agree, how should a reasonable person proceed? Often, one falls back on familiar ideologies, beliefs, and attitudes that can provide a measure of indirect guidance. Just as some people trust a doctor who has treated the family for three generations and others trust the young newcomer, such is also the case in public affairs. Those with a favorable attitude toward business, for example, tended to be reassured by the messages coming from the nuclear industry. Others who had shared Jane Fonda's views about Vietnam tended to trust her on the nuclear issue as well. This is still a rational response on the part of the public. If people can not understand an issue and the experts disagree, they side with those who share their views on issues that they do understand. This is admittedly a subjective kind of rationality, but it is often the only kind available, and it works fairly well in most domains of ordinary life and public policy. In this case, it led to a gradual reduction in support for nuclear power.

Then came Three Mile Island and other near misses. Although given reassuring interpretations by those with a knowledge of nuclear power, these events carried one dominant message to those without much knowledge: something is wrong. For years nuclear advocates inside and outside government had told the public that "it" could not happen, and then "it" almost did. This was much like a patient going into a coma during surgery that was supposed to be routine. The

public had been reassured that government regulations were adequate to ensure safety, but it seemed that they almost had not been at Three Mile Island. Against the backdrop of these years of reassurance, TMI had a devastating effect on the foundations for public acceptance of nuclear power—trust in the experts.

The well-publicized incidents at operating reactors, coupled with revelations of shoddy construction, questionable operator training, and poor maintenance at some plants, almost forced the public to move toward an increasingly skeptical position. What little evidence was available seemed to cast doubt on the credibility of those advocating the technology. The disarray among experts and the discrepant events like those at Three Mile Island were interpreted as a sign of uncertainty, and the sensible response to uncertainty in the face of a potential hazard is to be cautious, to ask whether the seemingly dangerous activity is really necessary. It is almost as if the public asked, "If we don't absolutely need this technology, and the experts don't have their act together, why take the risk?" This was not a precise trade-off of costs and benefits, but given the information available to the public it was not an unreasonable judgment.

We do not want to overstate the conclusion. Clearly, much of the public understands very little about nuclear power, and the judgments of many people about the relative risks of technologies cannot withstand simple tests of consistency. But from the perspective of a subjective rationality, it does not appear that the public did all that badly.¹⁸

Is Technology Too Complex?

The other point of view is that democracy is not up to the challenge of technology, because such issues are so much more difficult to deal with than nontechnology policy issues that they should simply be avoided whenever possible. They seem more difficult in two senses: they are less reversible, as the painful take-it-or-leave-it experience with nuclear power so aptly demonstrates, and they pose a potential for catastrophe. With the exception of issues arising during military crises, where decision making typically occurs outside nor-

18. For a related argument on the reasonableness of subjective rationality in appraising risky technologies see Charles Perrow, *Normal Accidents* (New York: Basic Books, 1985).

mal political forums, virtually no policy issues carry the degree of physical risk posed by large-scale technologies like nuclear power.

But that the problem is challenging does not make it insurmountable. On the contrary, in an earlier, comparative study of toxic chemicals, nuclear power, early biotechnology research, ozone depletion, and the greenhouse effect, we traced the evolution of a surprisingly sensible and sophisticated set of strategies for managing risky technologies.¹⁹ The strategies were not fully developed or employed in every case, and sometimes were more implicit than deliberate. Implementation was often underfunded or otherwise inadequate. But taken together the five strategies formed a more or less complete system for averting catastrophes.

The first strategy is to protect against any serious hazards that can be foreseen. Containment and remote siting of nuclear reactors before the mid-1960s are prime examples. Even though nuclear policy makers were quite uncertain about the exact dimensions of the risks they faced, there was no doubt that an accident could be sufficiently damaging to warrant precautions. Although this seems an obvious, elementary step, nuclear power was one of the first policy arenas where such precautions were taken from the outset rather than after bad experience.

A second, related strategy is to err on the side of caution in protecting against the potential hazard. People in all walks of life take out insurance, diversify investments, and otherwise seek protections. But often the tactics are adequate only to cover moderate levels of loss. This is usually appropriate, but in regulating risky technologies it is not enough; the uncertainties are sufficient to warrant being especially conservative until experience provides a better guide. In nuclear policy making, two tactics pursued in support of this strategy were wide margins for error and redundancies in reactor design.

Third, once cautious protections are in place for coping with the potential hazard, it makes sense to attempt systematically to reduce uncertainties about the character and magnitude of the risks. In the mid-1970s, for example, when controversy arose over risks associated

19. See Morone and Woodhouse, *Averting Catastrophe*, for further discussion of this concept of sophisticated trial and error. See also Edward J. Woodhouse. "Sophisticated Trial and Error in Decision Making about Risk," in Michael E. Kraft and Norman J. Vig, eds., *Technology and Politics* (Durham and London: Duke University Press, 1988), pp. 208-223.

with early biotechnology research (on recombinant DNA), a series of worst-case experiments were run to assess the likelihood that a genetically engineered organism could escape from the lab and survive in the environment. In effect, rather than wait to learn from experience whether their precautions were adequate, researchers and regulators chose to speed up the learning process. The equivalent steps were not taken in nuclear power, where the AEC's approach was to commission the Rasmussen study to "prove" that a reactor accident was a vanishingly remote possibility.

The fourth strategy is to learn from experience. This is critical for all policy making: information about the consequences of decisions should be actively monitored, and policies adjusted in response to that information. In the case of recombinant DNA research, for example, advisory committees actively monitored the experience of scientists experimenting with recombinant techniques, and recommended changes in regulations accordingly. Likewise, the Environmental Protection Agency now monitors the use of all new chemicals to determine whether their actual use conforms to that originally approved. In contrast, in the nuclear case, considerable active learning occurred in the 1950s when many types of reactors were being tried out; but when inertia set in learning became constrained, and only marginal changes to the existing approach were considered.

The fifth strategy is to set priorities. That is, because resources and attention are scarce, in employing the first four strategies one focuses first on the most important hazards or on the most cost-effective measures. In regulating new chemicals, for example, the Environmental Protection Agency has developed a system for focusing attention on the classes of chemicals that are likely to pose the greatest risks. A great shortcoming of nuclear power regulation is that it became mired in the details of one controversy after the other, and never seemed quite able to set priorities among the design changes and safety improvements that might or might not have been necessary.

Throughout the 1950s and early 1960s nuclear policy making generally conformed to these strategies for averting catastrophe, but later virtually every one was violated. This was most evident in the scale-up and dissemination decisions of the mid-1960s. The shift in safety strategy that deemphasized containment weakened the protections against potential hazards (in violation of the first strategy). And although certain aspects of reactor designs were made considerably

more conservative, overall it is impossible to characterize the pace of scale-up and dissemination as cautious (a violation of the second). Plans to test the consequences of serious reactor accidents were actually canceled as a result of the shift in safety strategy (a violation of the third).²⁰ Perhaps most important, the scale-up and great bandwagon market outraced the capacity to learn from experience: by the late 1960s utilities were ordering large numbers of reactors that were five times more powerful than any previously operated (a violation of the fourth). This in turn contributed to a stream of controversies about safety-related changes, which overwhelmed the Nuclear Regulatory Commission's capacity for imposing design changes in an orderly fashion (a violation of the fifth).

In short, the decisions of the mid-1960s were poorly made. They violated fundamental precepts for regulating risky technologies that policy makers in business and government had evolved in an array of technological arenas, including that of nuclear power. This was not a case of technology outstripping democracy; it was a case of democracy failing to live up to its own standards. The system for averting catastrophe evolved precisely because issues of technology policy often pose greater risks than many other issues, and can be very difficult to reverse. That is all the more reason to proceed carefully, air potential disagreements and missteps thoroughly, and move in small steps that allow learning from experience rather than in giant ones that make timely learning almost impossible. The United States did not proceed in this way at the critical stage in the development of nuclear power, and the outcome was miserable. But the nation has proceeded in a more sophisticated way at other times, and can do so even more systematically in the future if a political majority is willing to learn from experience.

Conclusion

The nuclear power experience reveals elements of several of the perspectives on technology and democracy introduced in chapter 1. But no existing perspective offers a good overall explanation of our findings.

Veblen and other technocratically minded social theorists were

20. See n. 38, chap. 5.

right to worry about the issue of competence. Although nuclear decision makers followed sensible strategies in the early years, at a critical juncture in the mid-1960s they did not. The technocratic view does not however help much in understanding why policies went astray. For example, technocrats would lament the extent of political and economic control over the nuclear enterprise, but at none of the crucial points in our story did experts recommend choices markedly different from those actually made. In particular, nuclear engineering experts failed to alert Congress to the implications of the scale-up. The demise of nuclear power therefore can hardly be attributed to society's failure to listen to the relevant experts.

The technological determinists likewise proved partly right, but mostly wrong. Those who see technology as a deterministic force have perhaps underestimated the potential malleability of sociotechnical systems. Many of us have implicitly assumed that nuclear power had to be taken as it was, rejected altogether, or modified by adding complex engineered safety systems to giant reactors. In fact, such social forces as a concern about communism and a desire for economies of scale shaped a diverse bundle of technical potentials into the form eventually taken by a major industry. The determinists were wrong insofar as nuclear technology was substantially shaped by social forces and at many points could have been further and better shaped by them. (The foregone option of inherently safe reactors is the most dramatic example of where that potential could have been realized.) But the determinists were right in that a particular form of nuclear power acquired technological, intellectual, and organizational momentum, and thus functioned temporarily as a deterministic force until stopped by public opposition and high costs.

Because decision makers allowed inertia to govern after 1965, Winner's concept of technological somnambulism is a fair characterization of aspects of nuclear policy making. In retrospect, the failure to debate the scale-up and rapid diffusion of nuclear technology was a form of political sleepwalking. Contrary to what might have been expected from this perspective, however, many of the earlier decisions about nuclear power were made about as deliberately as humans ever do anything.

Overall, the nuclear power experience suggests a somewhat more complex relationship between technology and democracy than that depicted by any of these social theorists. We find a fundamentally

greater compatibility between technology and democracy than do these other schools of thought. Yet at the same time we find much that is valid in them. Their most important contributions, combined with the insights we have gained from the history of nuclear power, suggest the following summary perspective:

- Technology is not an immovable force but a malleable one. The shape it has taken, the shape it might have taken, and the shape it may take are largely the product of human decisions. Yet large-scale technologies are subject to inertia, which tends to subvert normal democratic processes of learning. Once inertia sets in, the polity may begin to behave somnambulistically.
- Representative systems of government are capable of shaping technology into a socially acceptable form before inertia sets in. The United States did so in the early days of nuclear power, it does so with other risky technologies, and we find nothing in the behavior of the allegedly irrational public that suggests an inability to do so in the future. Yet decision making about large-scale technology is more difficult than decision making for many other domains, and in this respect technology does place stiff demands on democracy.

Whether society meets those demands is strictly a matter of how active and strategic it is prepared to be in designing technologies. At a critical juncture in the history of nuclear technology, it failed the test of competence. But there is no reason in principle why representative governments have to behave in this way. Decision making could have followed more sensible strategies in the mid 1960s. Scaleup could have been more cautious until enough was learned about the technology. Large-scale experiments could have been devised that would have narrowed the major uncertainties. Key decisions could have been better scrutinized and subjected to more debate. These are normal characteristics of democratic decision making.

Thus more democracy in the 1960s rather than less would have gone a long way toward making the nuclear technology of the 1980s more palatable. By the same token, the form taken by nuclear and other energy technologies in the future is potentially subject to deliberate political choice. We can continue to let technologies be governed by momentum, or we can be active, consciously shaping the form of technology (within limits) to conform with our goals, and those we seek to impart to future generations. If we find it more comfortable

to sleepwalk, it will at least be sensible to recognize that we are doing so by choice, rather than assume that we have none.

Some have concluded that technology is what ails democracy and others that democracy is what ails technology, but we find the two potentially compatible. If there is a villain in the relationship between technology and democracy, it is the passivity that periodically descends on representative democracies when faced with the task of shaping technology. When there are problems beyond those that normally attend complex human activities, this should not be interpreted as an inherent flaw in the technology or in public perceptions. Instead, such difficulties should lead us to suspect that democratic processes are failing to take advantage of the early malleability of technology and that inertia is setting in. The remedy is to liberate our technical and political imaginations, engage in deeper and more spirited political debate and inquiry, and actively reshape the technology to match public preferences better.

CHAPTER EIGHT

A Strategy for Democratic Control

The nuclear era began in an age of optimism, when technology seemed to hold the key to a wondrous future, perhaps even to energy “too cheap to meter.” In the United States, it is ending in bitter disappointment and cynicism, with little prospect of revival in the foreseeable future. Utilities have turned away from nuclear power, reactor vendors have greatly reduced their manufacturing capacity, the national laboratories have turned to new endeavors, and university departments of nuclear engineering—the source of new talent—are beginning to wither away or change their focus. Much of Europe also appears to be turning its back on the technology. Only a handful of nations outside the Communist bloc still intend to increase substantially their reliance on nuclear power, and there is reason to wonder whether even these will endure if there is another accident approaching the scale of Chernobyl. There are even indications that public opposition is slowing reactor construction in the Soviet Union.¹

In the face of all this, is it time to give up altogether on nuclear power? Many of course seem already to have made up their minds. But we suspect that thoughtful citizens and policy makers concerned about the greenhouse effect and other problems caused by fossil fuels

1. Bill Keller, “Soviet Scraps a New Atomic Plant in Face of Protest over Chernobyl,” *New York Times*, January 28, 1988, sec. A, pp. 1, 9; David R. Marples, *Chernobyl and Nuclear Power in the USSR* (New York: St. Martin’s, 1986).

will be scratching their heads a good deal in the next decade. For it is by no means obvious how best to combine environmental preservation with energy security and economic prosperity. As various political systems sort out their options, it would seem sensible to apply the lessons of the unsuccessful American experience with nuclear power. For although the first attempt has not worked out very well, it is entirely conceivable that some nations will decide to try again.

Victims of Inertia

Although one may question the major directions chosen for nuclear power in the 1950s, clearly the key decisions were made by legitimate elected representatives and their delegates, pursuing plausible versions of the public interest. All this changed in the 1960s; the rapid scale-up and diffusion of giant reactors were not based on any thoughtful partisan conception of good public policy. Instead, the American political process simply forfeited responsibility for intelligent guidance of civilian nuclear power, and it has not yet recovered. This was the one main, avoidable problem at the root of nuclear power's travails: political passivity at a crucial juncture allowed technological momentum to replace conscious shaping and reshaping of the technology. How to learn from that mistake is one of the main tasks now facing nations that have tentatively rejected nuclear power.

There is very little evidence of such learning to date. Large light water reactors with engineered safety systems remain predominant, not only in the United States but in most Western nations. The Nuclear Regulatory Commission focuses on their regulation, utility companies on their management and on the construction (or cancellation) of the few reactors remaining in the pipeline, and antinuclear groups on protesting against these reactors and seeking court injunctions against them. Even in the late 1980s, it was seldom mentioned that there might be attractive alternative forms of the technology.² In the news media and the public mind, "nuclear power" remained syn-

2. Even very good books on nuclear power rarely discuss inherently safe reactor concepts; see for example Joseph L. Campbell, *Collapse of an Industry: Nuclear Power and the Contradictions of U.S. Policy* (Ithaca: Cornell University Press, 1988). Actual misstatements are not uncommon, such as the claim that nuclear plants "are always large" in Matthew L. Wald, "New Debate about Nuclear Energy," *New York Times*, March 22, 1988, sec. 4, p. 17.

onymous with large light water reactors that can suffer catastrophic meltdowns.

The reactor industry shows little interest in a new approach. In part, it is reluctant to embrace a fresh start because doing so would imply that the current approach is indeed unsafe—a position the industry unreservedly rejects. It also realizes that providing nuclear power systems has not been a money-making proposition and may never be one. After more than two decades of losses it is unlikely that the vendors would be willing to put their own money into an effort to restructure the technology, let alone take the lead in such an effort. In fact, the remaining vendors seem to be losing interest in building reactors of any kind. Their businesses increasingly focus on the more profitable activities of providing fuel, spare parts, and other services to existing reactors. General Electric has even discussed the sale of its nuclear business.

Roughly the same lack of motivation characterizes the utility companies, many of which are reeling from their experience to date. There are a few notable exceptions, but given the dreadful experience that most companies and their stockholders have had with nuclear power, it is difficult to imagine utilities becoming strong advocates for a new and different form of the technology.

What about intellectual ferment within the technical community, where promising new ideas so often arise? There are pockets of creativity remaining, such as one team at the Massachusetts Institute of Technology that is promoting inherently safe reactors, but in general nuclear engineering in the university is beginning to die. As the Department of Energy's budgets have declined and the industry has entered the doldrums, sources of funds for creative research have dried up and the ability of nuclear engineering departments to attract fresh talent all but vanished. Meanwhile, the original sources of nuclear power in this country, the national labs, are aging and have been under severe budget constraints since the late 1970s. Altogether, there is no mass of talented researchers seeking creative ways to develop an acceptable form of nuclear power.

Thus the only real hope in the United States for serious exploration of a more acceptable nuclear future is the government. The Office of Science and Technology Policy and the Department of Energy held exploratory discussions on the subject in the mid-1980s, but no solid proposals emerged, even though the Reagan administra-

tion was the most solidly pronuclear administration of the past two decades. The administration's reluctance to get involved stemmed in part from the view that private enterprise should be responsible for any further development of the technology. The decisions of 1954–57 that turned civilian nuclear power over to competitive private enterprise have never been seriously reexamined. Even among those who favor this energy source, the prevailing assumption is that whatever is to be done is up to private enterprise. That was at least a halfway plausible idea in the mid-1950s, but it is just plain silly in the 1990s, for the reasons discussed above.

The path of least resistance is to perpetuate the pattern set in motion in the mid-1960s: allow technological momentum surrounding the current form of nuclear power to shape future policy. For all practical purposes, this means that nuclear energy will continue to decline in the United States. It will be revived only if coal turns out to be too dangerous, oil too scarce or expensive, and other options inadequate.

There is something to be said in favor of this approach. It is a more honest recognition of the limits of our ability to foresee the future than were the grandiose energy projections and massive programs developed by the Department of Energy in the 1970s, or the equivalent programs by Britain's Central Electricity Generating Board and France's combine of *Electricité de France* and *Framatome*. The Carter administration's program for spending billions of dollars in a crash program to develop liquid synthetic fuel from coal, for example, is perceived in retrospect to have been a boondoggle. The Clinch River Breeder Reactor likewise was an incredibly expensive project that could not lead anywhere the American electric power industry would want to go soon. Much the same can be said of large-scale energy projects borne of technological hubris elsewhere in the world. Phasing out nuclear power would avoid such schemes, end the political and financial quagmire, and ease the concerns of hundreds of millions of people in many nations; these are not trivial advantages.

An Alternative Path? Why Bother?

The present course passively accepts the alternatives created by flawed decision making in the past: either no nuclear power at all, or large-scale light water reactors with engineered safety situated near

populated areas. A working majority in most noncommunist nations have picked what they consider the lesser of the evils, choosing to forego further construction of nuclear power plants. That would be a plausible course of action if there were no other options.

But there are options. It appears technically possible to transcend the false dichotomy, the take-it-or-leave-it choice brought on by political passivity during the scale-up of the 1960s. At least in principle we can endeavor to reshape nuclear technology in line with criteria specified through a democratic decision process. Although only highly pluralistic decision making over several decades can determine what specific energy sources will be acceptable a generation or more from now, virtually everyone will agree that the world ought generally to aim for energy supplies that are safer, cleaner, and more enduring than those now available.

The United States has reduced its dependence on imported oil since the mid-1970s, but it still imports about a third of the five billion barrels of oil used each year. Domestic oil production peaked in 1970, and can be expected to decline gradually as reserves are exhausted. The oil shocks of the 1970s cost the American economy about \$100 billion in lost production, and the nation paid out approximately \$500 billion for imported oil from 1973 to 1988—roughly the amount of the trade deficit during that period.³ The present passivity toward nuclear power and other alternative energy sources amounts to rejecting protection against future oil shocks. Because global oil production and prices fluctuate dramatically in response to economic recessions and political upheavals, there will be commensurate fluctuations in the economic and social fortunes of nations that rely on a politically passive approach.

A passive energy policy also means vulnerability to the uncertainties associated with coal, which now provides more than half the electricity used in the United States, and a substantial portion of all the world's energy. Although the magnitude of damage caused by acid rain is still disputed, estimates of annual damages running to billions of dollars now appear credible, and coal combustion is believed to account for perhaps half the problem.⁴ Also unknown is the magni-

3. Walter A. Rosenbaum, *Energy, Politics and Public Policy*, 2d ed. (Washington: Congressional Quarterly Press, 1987).

4. The problem of acid rain and its possible magnitude are discussed in Sandra Postel, "Altering the Earth's Chemistry: Assessing the Risks," *Worldwatch* Paper 71

tude of climate warming due to the greenhouse effect; but when 1987 proved the warmest year of the warmest decade in the past century, researchers who expect severe effects within several decades gained credence. When the pattern continued into 1988, which was marked by droughts and record-breaking heat, the issue moved to the front pages and some analysts argued that the greenhouse effect was already beginning. Among other effects of a warmer earth, changes in rainfall patterns are expected to reduce the productivity of cropland in the Midwest, hurting farm states and raising the price of grain and meat.⁵

Coal also causes significant health problems, many of which are not yet widely understood among the general public. Mining and combustion of coal release substantial quantities of radioactivity, which at present are not tightly regulated. Lung diseases and other chronic health problems are inflicted in a relatively unpublicized way throughout the population by air pollution from coal combustion. In addition are the well-known environmental costs of coal mining, and the deaths and illnesses of underground coal miners. Altogether, coal poses a very substantial problem for industrial societies, and it is by no means inconceivable that a widespread movement to curtail its use will arise in the next generation.⁶

Also uncertain are the long-term prospects for natural gas. Analysts disagree vehemently on the prospects for solar energy, they differ on the likelihood of technical breakthroughs to increase energy efficiency, and there is little agreement on the extent to which lifestyles can be altered in response to energy shortages. Thus we cannot predict what energy the nation and world will want or need, nor what options will be available to meet the demand. It is conceivable that there will be enough options to render nuclear power unnecessary in many nations, but equally conceivable that there will not be. And if such difficulties as the greenhouse effect do force a shift away from coal, and financially feasible energy alternatives are not available, much of the world may be backed into a corner: either construct

(July 1986): 31ff; and James L. Regans and Robert W. Rycroft, *The Acid Rain Controversy* (Pittsburgh: University of Pittsburgh Press, 1988).

5. For a more detailed discussion of the problem of climate warming see Postel, "Altering the Earth's Chemistry"; and Joseph G. Morone and Edward J. Woodhouse, *Averting Catastrophe: Strategies for Regulating Risky Technologies* (Berkeley: University of California Press, 1986), chap. 6. See also n. 63, chap. 1.

6. Rosenbaum, *Energy, Politics, and Public Policy* and sources cited therein.

rapidly a new generation of giant light water reactors, feared by a substantial portion of the population, or face the economic and other consequences of extremely tight energy supplies.

No intelligent society would allow itself to be confronted by such a take-it-or-leave-it choice as its primary energy option. In the 1970s and 1980s technological inertia froze nuclear power technology into an unacceptable form, and circumstances then forced a take-it-or-leave-it decision. One of the main goals of future energy policy making should be to avoid such unhappy, all-or-nothing choices. Japan is one of few nations working creatively to avoid such a scenario, by investing heavily in energy research and development. Rather than hope for the best, it is preparing for the worst. Rather than passively allow events and technological inertia to rule, the government has developed a long-term energy plan. Whether it is a good plan is a matter for debate, but at least the Japanese system is acting in accord with one of the main lessons of the American nuclear power experience: actively shape technologies to serve social purposes.

Shaping Nuclear Technology: A Strategy

If representative governments have a second chance to shape nuclear technology and its associated organizations, what should they endeavor to do better than the first time around? In particular, what strategies should they employ in developing an acceptable reactor type and approach to safety, scaling up that technology, and devising a structure of ownership, management, and regulation?

Process of Reactor Development

The first step toward a publicly acceptable form of nuclear power would be to turn on its head the premise that guided the first research efforts: instead of developing economical reactors engineered to be as safe as possible, develop safe reactors engineered to be as economical as possible. The world's nuclear engineers have numerous ideas for going beyond the types of reactors and safety systems that have proven unacceptable (see chapter 6). It is not known for certain whether any of their ideas will work, though a number seem promising. And no one can know in advance which of the various proposals will prove superior. But it seems obvious that the current form of nuclear technology is not nearly the best that humans can devise.

What sort of process would make sense for exploring the PIUS reactor, the pebble bed reactor, and other options that might be available for more acceptable nuclear reactors? We suggest a modest program of research and development funded at a level of perhaps \$100 million to \$200 million a year during an exploratory phase that would last about a decade. This is less than half the amount expended weekly by the United States for imported petroleum in 1988.

Such a program would be sufficient to rejuvenate the best nuclear engineering departments at leading universities, providing funds for faculty research as well as fellowships for graduate students. The funds would also allow a substantial increase in the Department of Energy's fledgling project with the Electric Power Research Institute, aimed at developing improved reactors. Expenses and results might be shared internationally, especially because several other nations are now ahead of the United States in working on new types of reactors.

After perhaps a decade, the program will have developed far enough for legislators, environmentalists, nuclear experts, and citizens to decide whether the new form of nuclear power appears sufficiently promising to advance to a second phase. By this point, the dangers of coal and the promise of alternative sources of energy will be somewhat clearer, so that any decision about nuclear power's future can be based on fuller information than if the decision were made today. If the polity decided to take another step—still not committing itself to full-scale use of the reformulated technology—the second phase would involve building large enough reactors for thorough safety and reliability experiments to be conducted at a remote test site. Every phase of this process should be open to scrutiny and assessment by antinuclear groups, the Office of Technology Assessment, independent experts, the news media, and others. Opponents of the new reactor might even be allowed to stage a worst-case accident at the remote test site, and the test might be televised; if the new reactor survived without damage, as proponents now claim it would, many skeptics might rethink their opposition to nuclear power.

Process of Scaling Up

If the public decided after observing and debating the test results that the new form of nuclear technology was acceptable, and if options such as coal came to be considered less desirable, how could the United States do a better job of learning about initially unforeseen

difficulties the second time around than it did during the first? We suggest that the key is to deliberately structure the middle phases of the process to promote learning.

This is where decision makers went astray in the 1960s, essentially declaring commercial nuclear power to be a success, and not paying attention to the scale-up and diffusion process. It may well be that scale-up in the size of reactors will not be the key issue whenever decisions have to be made about whether to begin regular electricity generation with the new technology. The research and development program could show that the reactors have to be kept small for technical reasons or conversely that large size is not a problem. But with virtually every complex new technology, the early years of routine operation bring some kind of surprise not discerned by testing prototypes. Therefore, whether by slow scale-up or other means, a crucial element of a more successful approach to nuclear power would be to structure the diffusion phase to promote early learning about problems—and correction of them.

Even if there were no problem with scaling up the size of reactors, for example, there would need to be careful attention to the rate of expansion in the number of units operating. Most technological problems are relatively manageable so long as the number of episodes or units is small enough to monitor carefully. Before the number grows too large, those responsible for the technology need to uncover and correct whatever difficulties await. For once a technology is in widespread use, inertia sets in: correcting errors entails much larger costs, and the organization responsible for the technology tends to resist imposing them.

How can environmental groups and other watchdogs make sure that a new technology such as reshaped nuclear power expands slowly enough and otherwise learns effectively? We unfortunately have no formula to offer. The most reliable method is to develop a widespread recognition throughout technological societies of the inevitability of errors in complex endeavors, and the consequent need to prepare for effective monitoring and learning. This will often mean proceeding slowly whenever possible. One government program that approximates this ideal is in the field of biotechnology, where each new release of genetically engineered organisms is supposed to be carefully scrutinized; another is the screening that the Environmental

Protection Agency now gives to every new chemical before it can be manufactured.⁷

These programs each embody the obvious but widely ignored insight that one way to reduce greatly the uncertainties about a new technology is to test for possible problems. Instead of waiting passively for bad experience to reveal errors, it makes sense to speed up learning and evaluation as much as possible. Whereas the first nuclear debate consisted of interminable battles about the conceivable behavior of reactors in hypothetical accidents, if there is a next time far more testing should be conducted under actual operating conditions. Some of this can come in the early phases, as discussed above. But that is not enough. Once the technology is actually being used, a broad testing program should continue. One important aspect of it would be to license nuclear reactors the way we do aircraft: test every one. In other words, "Because an inherently safe reactor will survive a worst-case accident without damage, . . . you could actually try out each reactor and prove it won't melt down. Such license-by-test is absolutely essential if the American public is ever again to accept nuclear power."⁸

The first nuclear power era may come to be seen in retrospect as one of the last vestiges of a tendency to rush blindly into new technical opportunities, relying too much on naive trial and error to reveal eventual difficulties. In a second nuclear era, if there is one, participants will want to prepare actively to learn from error. This is partly a matter of deliberate strategy, as in the case of license-by-test; equally, though, it is a matter of the spirit in which a new endeavor and its problems are evaluated and reshaped. The first time around, neither the spirit nor the strategy was adequate. Entrenched positions by partisans on both sides of the issue prevented constructive reshaping of the technology once problems became evident; this need not happen again.

Devising an Institutional Structure

How well decision makers learn about a new form of nuclear power will depend partly on the institutional incentives given to the

7. Morone and Woodhouse, *Averting Catastrophe*, chap. 2.

8. Lawrence M. Lidsky, "Safe Nuclear Power," *New Republic*, December 28, 1987, p. 23.

owners, managers, and regulators of the technology. From this point of view, one of the lessons of the American nuclear power experience was that the ownership and organization of the industry was ill conceived. In the future, rather than base industry structure on ingrained habits, prevailing ideologies, or other external criteria, it would make sense to structure technological endeavors on the basis of the goals they are intended to achieve.

Admittedly, this was done to some extent in 1954 when the Atomic Energy Act was revised, for legislators wanted faster development of civilian nuclear power and believed that competitive private enterprise would deliver it. The same may be said of the Price-Anderson Act of 1957 that limited the nuclear industry's liability in case of an accident; this was explicitly designed to remove a disincentive that was interfering with legislators' goals. But an ideological belief in the universal efficacy of private enterprise clearly outweighed sober appraisals of the best way to pursue civilian nuclear power, and the debates of the 1950s did not consider thoroughly the broad range of values involved.

Later the situation became even worse; Congress as a whole never again seriously debated the fundamental structure of the nuclear industry. Although the Joint Committee on Atomic Energy held extensive annual hearings on the progress of commercial nuclear energy, it did not carefully weigh and debate options for restructuring it to give added weight to safety or other values. The issue of ownership and management structure was essentially settled in 1954-57, well before there could have been sufficient experience with the new technology to make final decisions on the subject.

What considerations should guide an effort to do better in structuring a second nuclear era? First, it is implausible to assume that one institutional form—competitive private enterprise—is good for every purpose. Amtrak was formed precisely because private enterprise was not succeeding in providing adequate rail service; American Telephone & Telegraph for many years provided interstate telephone service as a monopoly; the space program was basically a government-run endeavor, with semicompetitive bidding by private contractors. Clearly, there are many possible organizational structures that could develop new reactors and generate electricity with them. Thoughtful debate about their relative merits is needed.

Second, it is doubtful that competitive private enterprise can be

the organizational form for taking the lead into a second nuclear era, for reasons already discussed. Quite probably, however, a new nuclear enterprise would rely on competitive bidding from private firms to supply parts and do much of the construction. And the existing system of investor-owned utilities would presumably be the customers for power generated by a new kind of nuclear plant.⁹ But we expect that a relatively centralized organization should be responsible for overall management, during the developmental stages and perhaps even once the plants are operating.

Third, the appropriate organizational structure depends in part on what criteria the system is intended to satisfy. The first time around, Congress preferred quick and economical over acceptably safe and reliable. We presume the order would be reversed if nuclear power is rejuvenated. But it is not for us or any few people to specify the criteria and organizational structure: these should evolve from an extended inquiry and debate among a variety of partisan interests. Our point is simply that the nuclear industry's organizational structure made a crucial contribution to the demise of the first nuclear era; to be more successful next time, it will make sense to choose an organizational structure on the basis of what the political majority is trying to achieve, rather than on the basis of habit.

Most people who entertain thoughts of nuclear power as a viable energy source for the twenty-first century seem still to hope for a miraculous recovery of the nuclear enterprise as we have always known it: large light water reactors, with engineered safety, owned and operated by the existing private-enterprise system of vendors and utilities, and overseen by government regulators. Nuclear advocates sometimes suggest that repeated electricity brownouts, another oil crisis, or otherwise serious energy shortages will "bring the public to its senses." This strikes us as a macabre hope; although such a scenario is conceivable, it is hardly the basis for a nation's energy policy.

Another typical hope is that some sort of reform of the regulatory system might save the nuclear enterprise, as expressed in repeated calls to streamline the regulatory process by introducing one-step licensing and replacing the unwieldy five-person Nuclear Regulatory

9. But hints of a new trend toward public power emerged in the late 1980s, as discussed in Philip S. Gustis, "Taking the Electric Power Business Public," *New York Times*, May 1, 1988, sec. 4, p. 28.

Commission with a more hierarchical structure.¹⁰ The regulatory system is indeed badly in need of overhaul, but it should be obvious by now that regulatory reform offers a band-aid to a patient needing a tourniquet. If nuclear power is to have a reasonable chance of being viable, we must resolve the public's legitimate concerns about the potential that large reactors pose for catastrophe. As Lawrence Lidsky expresses it, "We thought we were having a great national debate over nuclear power. Instead we have merely been discussing the acceptability of the LWR. But the LWR is no more a surrogate for the potential of nuclear power than the Hindenburg was for the potential of air transportation."¹¹

We think it makes little sense to stay with the current approach to nuclear power. Too many people are afraid of it. And whether or not one agrees with their concerns, such a large number of people deserve to have influence on future energy policy. The research and development program outlined above would explore the prospects for a more acceptable form of nuclear power in a way that melds the best insights of the antinuclear forces (nuclear power should be safer and more acceptable) with the best insights of the pronuclear forces (the world needs a better way of generating electricity than the present coal technology).

An active political approach to reshaping nuclear power technology is also compatible with the kind of strategy for intelligent decision making that has evolved in several areas of technological regulation (see chapter 7). The essence of that strategy is that the uncertainties in energy and other technological policy arenas are so high, and the results of error potentially so severe, that good decision making requires a coping strategy instead of blind trial and error. In particular, we need to protect carefully against foreseeable risks, and prepare actively to learn. This approach was followed fairly well in the early years of American nuclear power, but lost sight of in the 1960s and after. It is time to return to it. By pursuing a modest research and development program directed at a new type of politically acceptable reactor technology, we would be hedging against the possibility that coal will turn out to have effects on climate and the ecosystem as severe as coal's opponents now suggest, that oil will be even scarcer and costlier than most analysts now fear, and that alter-

10. OTA, 1984.

11. Lidsky, "Safe Nuclear Power," p. 23.

native technologies will not work out as soon or as well as their proponents now believe.

To put it differently, more intelligent and more democratic control of technology will be necessary to avoid repeating the errors of the past. Political passivity in the 1960s allowed technological inertia to mold an unsatisfactory set of options: either no nuclear power at all, or very large reactors with engineered safety systems that might fail. A technology with even a small potential for catastrophe has now been rejected by virtually every nation where vocal citizens can translate their dissatisfactions into public policy; but our imaginations and energy policies remain trapped by technical, organizational, and intellectual inertia. And the longer we keep the state of mind inherited from an earlier generation, the more we compound the costs of unfortunate decisions made long ago.

Admittedly, the odds of revising the inherited approach do not look very favorable, and the feasibility of reshaping the technology into an acceptable form is not fully knowable until we try it. But just as nuclear power technology was initially shaped by political and economic forces a generation ago, so it can be reshaped if a political majority becomes willing to undertake the task. Now that they have won the battle, will those who opposed large-scale nuclear power turn away from energy issues altogether? Are those who favored nuclear power so dispirited that they will withdraw from active efforts? If so, the fundamental error of the first nuclear trial will endure, with political passivity allowing technological inertia to force unsatisfactory policy options on society. In contrast, pronuclear and antinuclear forces can choose to recognize that energy technologies are highly malleable (though not infinitely so), and that democratically selected criteria can be used to reshape technologies. We saw evidence of such shaping in the early years of nuclear power, and further evidence of the power of politics over technology as citizens' groups rejected large-scale nuclear power. Those who value intelligent, democratic control of technology need to begin working soon if they want political inquiry, debate, and judgment to shape future energy policy. For inertia now has the upper hand.

APPENDIX

Understanding Nuclear Power Technology

Probably not one person in a hundred who has a strong opinion about the future of nuclear power understands how a reactor works. Although the complete technical details are beyond the reach of nonexperts, a working view of the subject is readily obtainable. This appendix explains how a reactor works and what the different types of reactor are.

Reactor Technology

Nuclear power plants generate electricity in much the same way as power plants that burn coal, oil, and natural gas. All such plants produce heat, use the heat to boil water and create steam, and use the steam to run a turbine; the turbine generates the electricity. The difference between nuclear plants and fossil fuel plants is the source of the heat. In a nuclear plant the heat is produced by nuclear fission.

The Chain Reaction

Fission occurs when a neutron strikes a uranium nucleus and causes it to split into two lighter elements, called fission products. As the uranium nucleus splits, it releases energy and several neutrons (2.5 on average). If some of these neutrons strike other uranium nuclei, they will cause additional fissions; and if neutrons released in

this second set of fissions strike yet other uranium nuclei, still more fissions will occur. This process is known as a chain reaction.

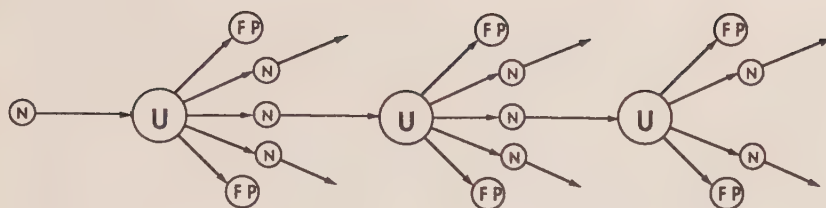
The amount of energy released in a chain reaction depends on the rate at which uranium atoms fission, and the rate of fission depends on how many of the neutrons released with each fission strike new uranium nuclei. If at each step in the chain reaction only one of the 2.5 neutrons released with each fission strikes another uranium nucleus, the rate of fission and the consequent power level remain constant. This is the sort of chain reaction that occurs in power reactors (fig. 1). If however most of the neutrons released with each fission strike new nuclei at each step in the chain reaction, the rate of fission and the energy level increase rapidly. This is the sort of chain reaction that occurs in a bomb (fig. 2).

It takes about 100 billion fissions a second to release enough energy to produce one watt of electricity. Obviously each fissioning atom releases only a tiny amount of energy, and a chain reaction in even the smallest of reactors comprises an enormous number of fissioning atoms. Control rods containing boron or another neutron absorber keep the chain reaction at the required level of steady activity. When inserted all the way, the control rods shut down the chain reaction altogether.

Fuel

Of course the process is a good deal more complicated than this. To begin with, most uranium atoms do not fission when struck by neutrons. Naturally occurring uranium is a mixture of two isotopes, U-238 and U-235. U-238 accounts for 99.3 percent of the mix. But U-238 does not fission; when struck by a neutron it simply absorbs it. Only the much scarcer U-235 isotope fissions. As a result, it is difficult to sustain a chain reaction in a reactor fueled with natural uranium. Because U-235 is surrounded by so much nonfissioning U-238, the neutrons released when a U-235 nucleus fissions are far more likely to be absorbed by nonfissionable U-238 than to strike and fission the U-235. And if too many neutrons are absorbed by the U-238, the chain reaction ends.

A common solution to this difficulty is to increase the percentage of U-235 in the fuel. This is known as enrichment. In contemporary American power reactors, the fuel is enriched to about 3 percent



N = Neutron
 U = Uranium
 FP = Fission Product

Figure 1

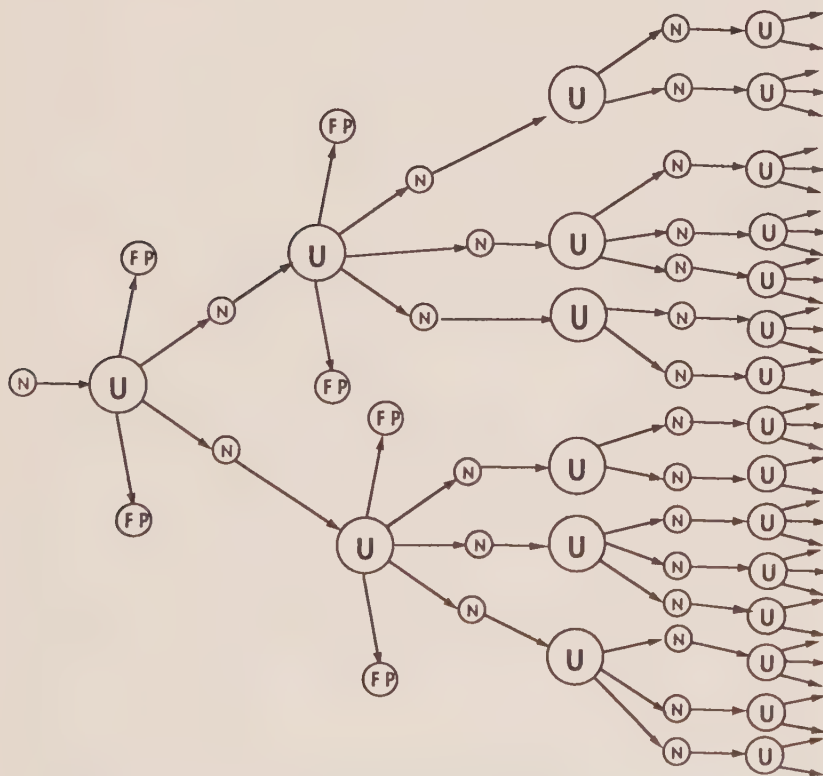


Figure 2

U-235. In bombs, the fuel is a great deal more enriched.¹ Because reactor fuel is much less enriched than necessary for a bomb, reactors cannot cause atomic explosions. There can be *chemical* explosions at a reactor, however, usually involving hydrogen or steam. The reactor at Chernobyl was destroyed by such an explosion.

Moderator

The likelihood of maintaining a chain reaction is also a function of the energy, or "speed," at which the neutron is traveling when it strikes the U-235 nucleus. Neutrons emitted when a U-235 nucleus fissions are traveling rapidly, and are less likely to cause an additional fission than are neutrons traveling at lower speeds. To slow the neutrons, in many reactors the neutrons are moderated.

The process by which neutrons are moderated can be illustrated by an analogy to the game of billiards. A fast neutron is like a cue ball: "In billiards a rapidly moving cueball entering a net of other balls is quickly slowed down by collisions; its energy of motion is transferred to the other balls as they recoil from these collisions. The moderator in a reactor works in much the same way: neutrons are slowed down by collisions with the nuclei of which the moderator is composed because the struck nuclei recoil away, taking up some of the energy."²

If it is to be effective, the moderator "must consist of nuclei not much more massive than a neutron."³ This too can be illustrated by the analogy to billiards. If the cue ball strikes a heavier object (such as the side of the table), it will not slow down appreciably, for the heavy object does not recoil on collision and therefore does not absorb much of the cue ball's energy. The cue ball is slowed down only when it strikes objects of similar mass, such as other billiard balls. The lighter objects will recoil as they are struck by the cue ball, and as they recoil they absorb some of the cue ball's energy. It follows from this analogy that only the lightest elements in the periodic table can

1. The process by which uranium is enriched is expensive, requiring enormous plants. The first enrichment plants were built during the atomic bomb project in World War II. Indeed, the bulk of the Manhattan Project was directed at developing and constructing enrichment plants.

2. B. L. Cohen, *Nuclear Science and Society* (New York: Anchor, 1974), pp. 84-85.

3. *Ibid.*, p. 85.

be used as moderators—those with nuclei most similar in mass to a neutron.

Further, the moderator must be of the sort of material that can slow down neutrons without absorbing them. If the moderator absorbs neutrons, fewer neutrons will be available to maintain the chain reaction.

Coolant

The fuel and moderator are placed in the reactor core. As the moderated neutrons strike the fuel, the fuel fissions and generates energy in the form of heat. The heat must then be removed from the core by the reactor coolant.

There are two main variations in the process by which the coolant removes the heat. One variation is illustrated by the pressurized water reactor, one of the two types of reactor in widespread use in the United States (fig. 3). The coolant in this reactor is pressurized water (as is the moderator). This pressurized water is pumped through the core, where it is heated. From the core it is pumped to the steam generator. There it passes through cooler water and boils it. The steam produced by this boiling water is then used to run a turbine, which generates the electricity. After the steam passes through the turbine, it is condensed into water and pumped back into the steam generator. Meanwhile, after the coolant passes through the steam generator, it is pumped back into the core.

The other main approach to cooling is used in the boiling water reactor, the second of the two reactor types in widespread use. The coolant here is relatively low-pressure water. When pumped through the core and heated, the water boils, generating steam. This steam then passes directly to the turbine. In this variation there is no steam generator: the steam that runs the turbine comes directly from the core.

Breeding

We have seen that energy is released when uranium fissions; that a chain reaction is sustained when one of the 2.5 or so neutrons emitted with each fission strikes a U-235 atom; that the probability of U-235 fission increases when the neutrons are moderated; and that heat generated by the fissions is removed by the coolant. There is one

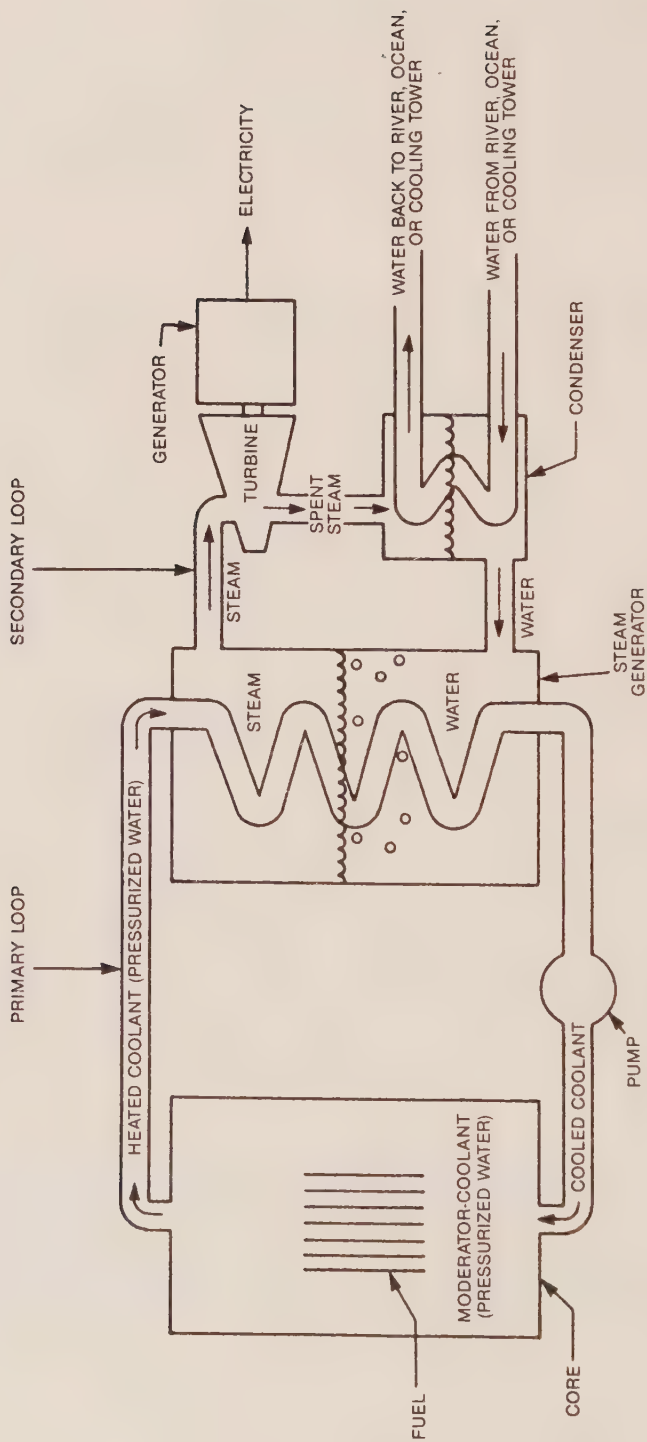


Figure 3

further complication: we have accounted for only one of the 2.5 neutrons released with each fission. We must still account for the remaining 1.5.

Some of the remaining 1.5 neutrons are simply wasted. They either escape from the core or are absorbed by materials in the core, such as fission products, moderator, and coolant. But others strike U-238 atoms, and these neutrons play an important part in reactor technology. When struck by neutrons, U-238 does not fission. Instead, it absorbs them and then decays into a new element: plutonium (Pu). Now whereas U-238 is not fissionable, plutonium is. Thus when a neutron is absorbed by a U-238 atom it is not simply wasted; rather it produces a new fissionable atom.

If more than one neutron is absorbed by U-238 for every neutron that fissions U-235, then more plutonium will be created than U-235 consumed. This process of creating fissionable atoms is called breeding. The significance of breeding is that it can greatly increase the percentage of natural uranium usable as reactor fuel. Instead of only the U-235, breeding enables a reactor to burn also the U-238 that accounts for more than 99 percent of the natural uranium.

To illustrate the process, consider a breeder reactor in which 1.1 neutrons are absorbed by U-238 atoms for every neutron that fissions a U-235 atom. As the small amount of U-235 fissions, 1.1 times as much U-238 is converted to plutonium. This plutonium can then be used as fuel in place of the consumed U-235. Now the process repeats itself, this time with plutonium atoms fissioning rather than U-235. For every neutron that strikes and causes a plutonium atom to fission, 1.1 neutrons are absorbed by U-238 atoms, which decay into new plutonium atoms. By the time the original plutonium is consumed, 1.1 times as much new plutonium has been produced. This process can continue until almost all the U-238 has been converted into plutonium. Thus instead of only the original, small amount of U-235 being used as fuel, almost all the uranium is used—U-238 as well as U-235.

It is extremely difficult to develop reactors in which a ratio of more than 1:1 is achieved. In most reactor types, and in all contemporary commercial reactors, less than one neutron is absorbed for every one that causes fission. So few reactor types breed, and no contemporary commercial reactors do.

Reactor Types

Following from the above, reactors can differ in any or all of the following categories:⁴

- Fuel type
- Neutron speed
- Moderator
- Coolant
- Geometry.

FUEL TYPE. The only naturally occurring fissionable material is U-235. Two other fissionable materials can be bred: plutonium (bred from U-238) and U-233 (bred from thorium). Thus there are three possible types of fuel—U-235, U-233, and plutonium—and two natural materials from which fuel can be bred—U-238 and thorium.

NEUTRON SPEED. The probability of fission varies with the speed at which the neutron is traveling when it strikes the nucleus. The optimal speed varies with purpose. For instance, if the purpose of a reactor is to breed plutonium, fast neutrons are usually preferred. But if the purpose is to propel a submarine, slow neutrons are more appropriate. There are three possible categories of neutron speed: fast, resonance (intermediate), and thermal (slow).

MODERATOR. If intermediate or low speed is desired, the neutrons released in each fission need to be moderated (slowed down). Moderating material must meet two criteria: the mass of its nuclei must be similar to the mass of a neutron, and its nuclei must have a low affinity for neutrons. The materials that satisfy both criteria to varying degrees are light (ordinary) water, heavy water (water enriched in the hydrogen isotope deuterium), carbon (graphite), beryllium, and beryllium oxide.

COOLANT. The heat generated in the reactor core must be re-

4. We refer here only to the broadest differences among reactor types. There are also innumerable variations among reactors that are of the same fuel type, neutron spectrum, moderator, coolant, and geometry.

moved, either to the steam generator or directly to the turbine. The appropriate material for this function must have good heat transfer properties and, again, a low affinity for neutrons. The materials that satisfy both criteria, also to varying degrees, are light water, heavy water, liquid metals, gases, and organic materials, such as hydrocarbons.

GEOMETRY. There is one final respect in which reactors can differ. In the types of reactors discussed so far, the fuel is submerged or embedded in the moderator, and both are held in place in the core; only the coolant circulates. Such reactors are called heterogeneous reactors. In a different set of reactor types, known as homogeneous reactors, the fuel and moderator are mixed in a solution. This solution, rather than a coolant, circulates through the reactor. As the solution passes through the core, the fuel in it fissions. The heat generated by the fission is then carried from the core to the steam generator by this same solution. After the solution passes through the steam generator, the spent fuel (now in the form of fission products) is removed, fresh fuel is added, and the solution is then circulated back into the core.

These categories are not entirely independent of one another. Choices made with respect to one category frequently constrain the choices that can be made in other categories. For instance, if a high neutron speed is chosen, no moderator is required, and only sodium and gas can be used as coolants. If the categories were independent, there would be 450 possible combinations of categories and therefore 450 possible reactor types ($3 \times 3 \times 5 \times 5 \times 2$). When dependencies are taken into account, the possibilities are reduced to about "100 combinations which are not obviously unfeasible."⁵ No doubt many of these can be eliminated on practical grounds, but even after this step there remain dozens of plausible reactor types. Some that have been proposed are given below:⁶

5. A. Weinberg, "Survey of Fuel Cycles and Reactor Types," *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy*, vol. 3, p. 23. Our more general argument about variety of types also is adapted in part from Weinberg.

6. See for example U.S. Congress, Joint Committee on Atomic Energy, *Hearings on AEC Authorizing Legislation for Fiscal Year 1958*, 85th Cong., 1st sess., 1957, p. 523.

- Boiling light water
- Pressurized light water
- Pressurized heavy water
- Boiling heavy water
- Pressurized water-cooled, graphite-moderated
- Sodium-cooled, heavy water-moderated
- Gas-cooled, heavy water-moderated
- Gas-cooled, graphite-moderated
- Sodium-cooled, beryllium oxide-moderated
- Sodium-cooled, beryllium-moderated, intermediate-speed
- Organic cooled, graphite moderated
- Organic cooled and moderated
- Sodium-cooled, fast
- Molten plutonium, fast
- Aqueous homogeneous
- Molten salt homogeneous
- Liquid metal-fueled homogeneous
- Fluidized bed or fixed bed, particulate fuel

At least as important as the differences in reactor types are the differences in the way any particular reactor type can be designed. The possible configurations are innumerable, depending for example on the conservativeness of design and the size of the reactor. Such "engineering" differences play a significant role in the fate (past and future) of American nuclear power, as the second half of this book makes clear.

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